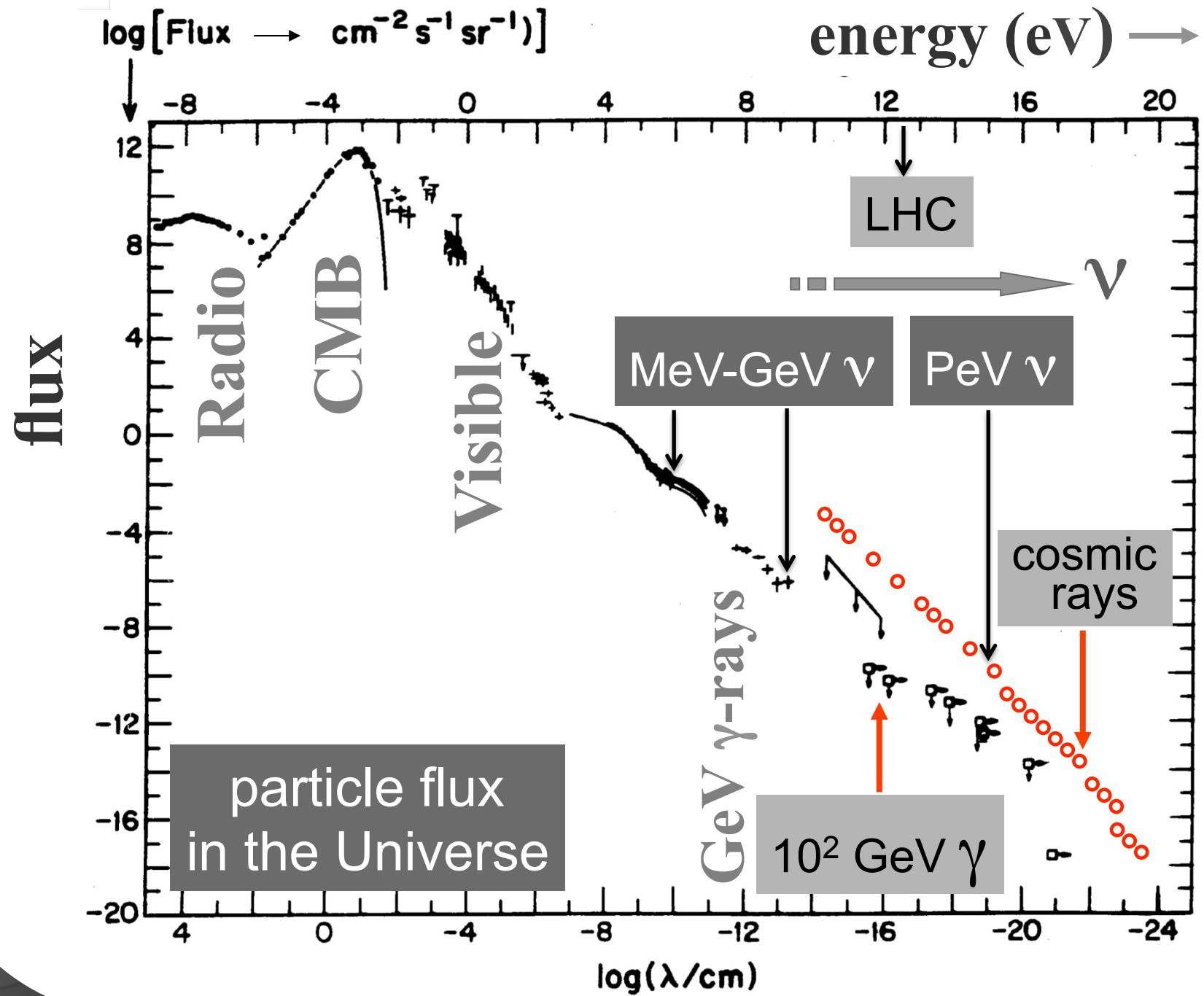


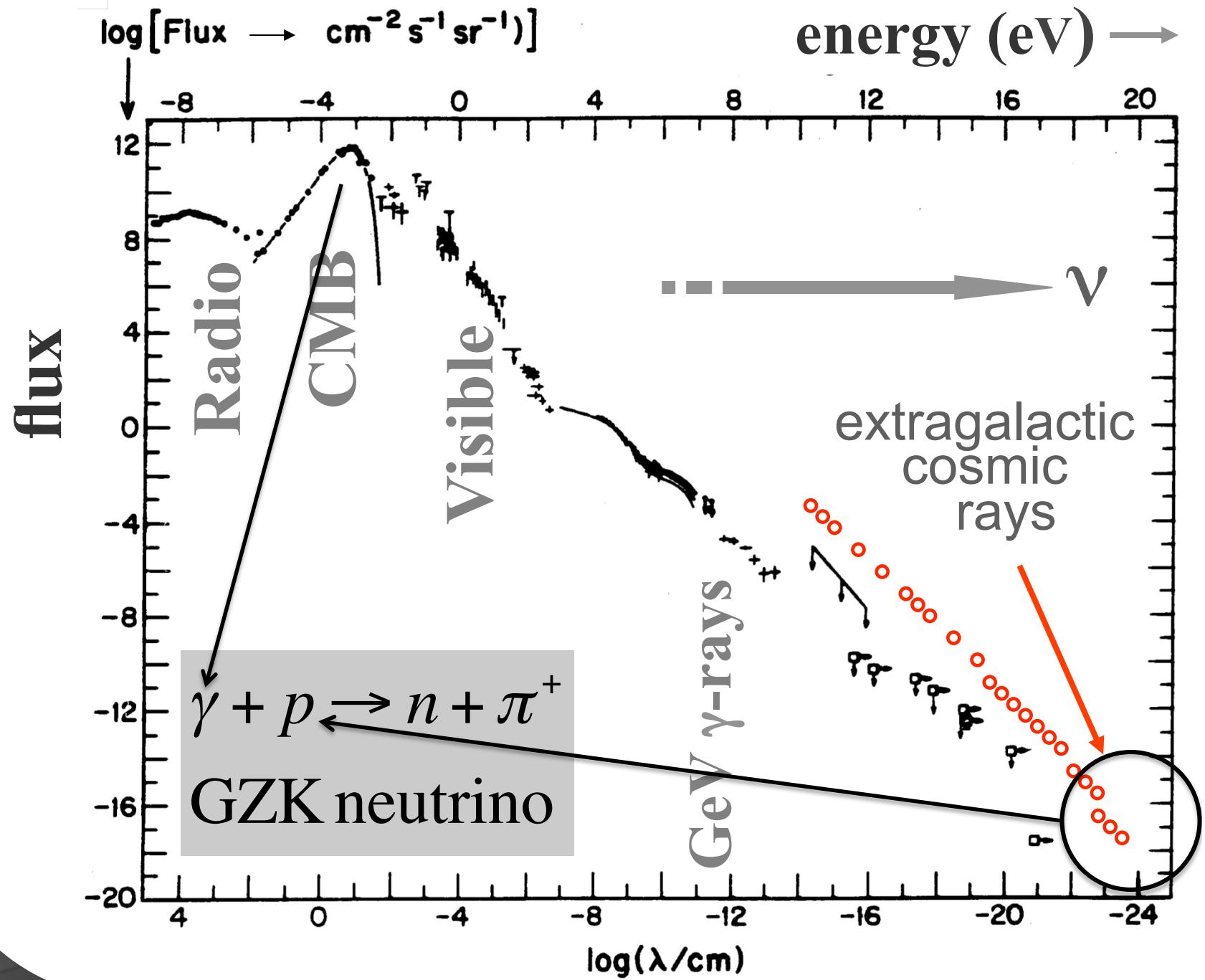


IceCube

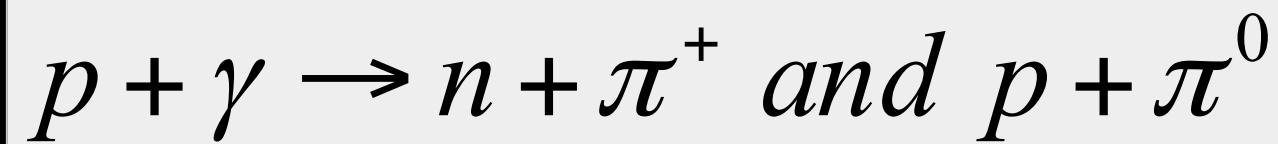
francis halzen

- why would you want to build a kilometer scale neutrino detector?
- IceCube: a cubic kilometer detector
- the discovery (and confirmation) of cosmic neutrinos
- from discovery to astronomy

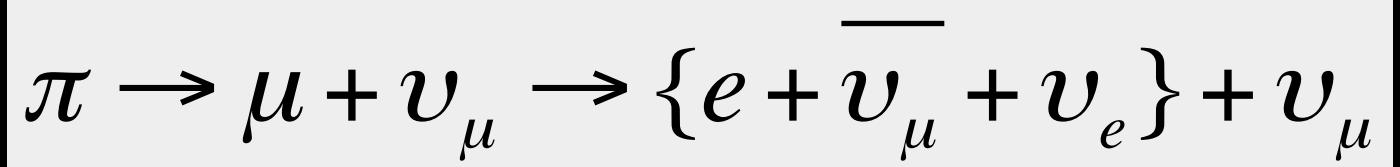




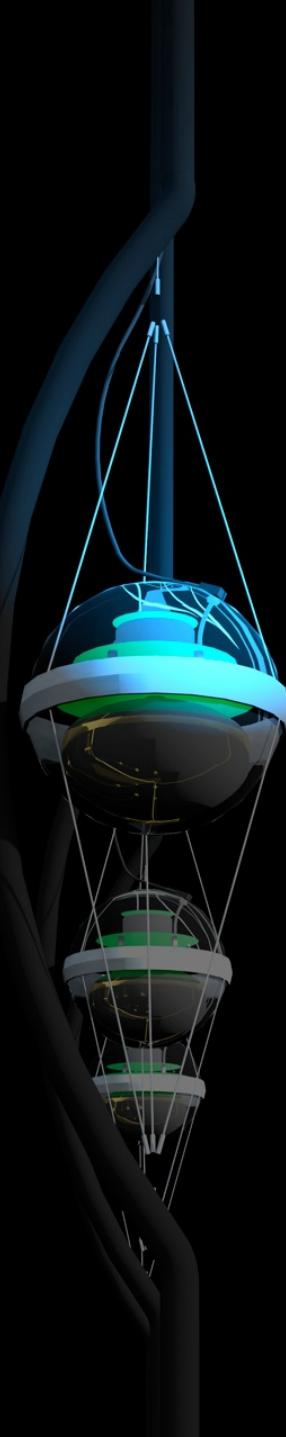
cosmic rays interact with the microwave background



cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear



1 event per cubic kilometer per year
...but it points at its source!



IceCube

francis halzen

- cosmogenic neutrinos
- the energetics of cosmic ray sources
- neutrinos associated with cosmic rays
- a cubic kilometer detector
- evidence for extraterrestrial neutrinos
- conclusions

- accelerator must contain the particles

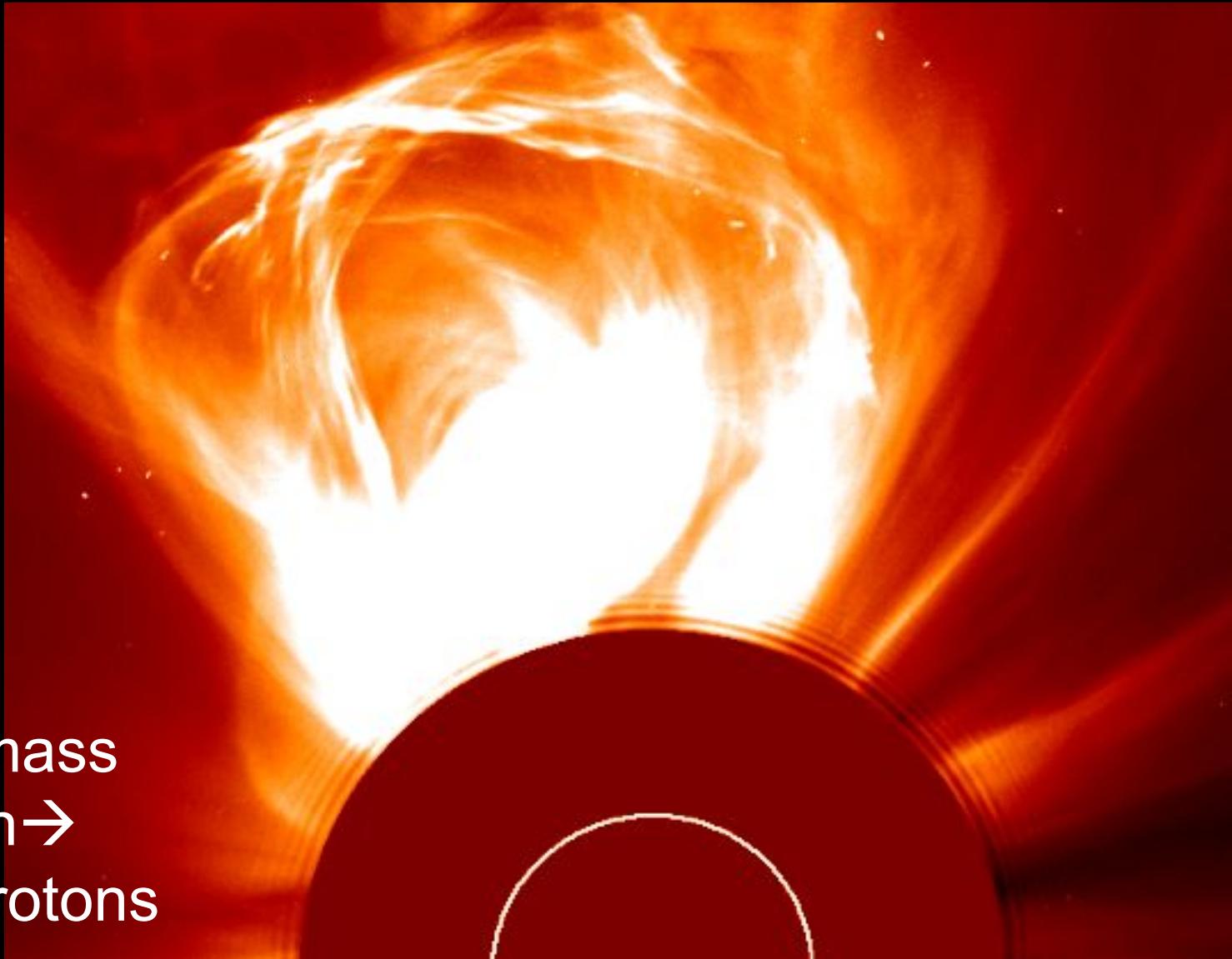
$$R_{gyro} \left(= \frac{E}{vqB} \right) \leq R$$

$$E \leq v q B R$$

challenges of cosmic ray astrophysics:

- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

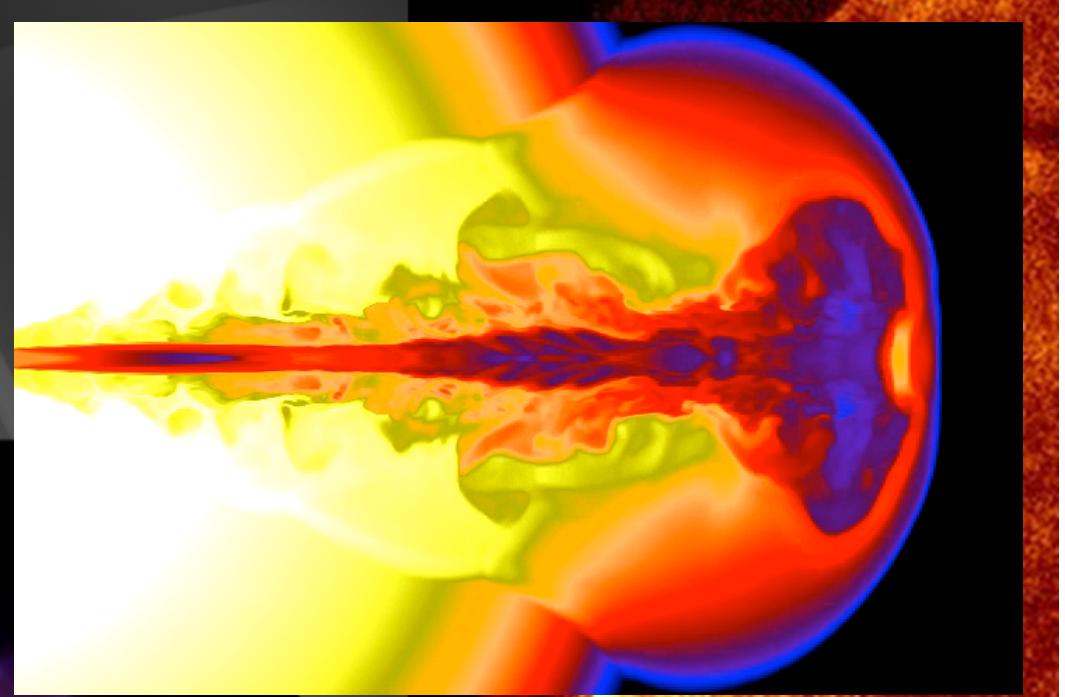
the sun constructs an accelerator



coronal mass
ejection →
10 GeV protons

supernova remnants

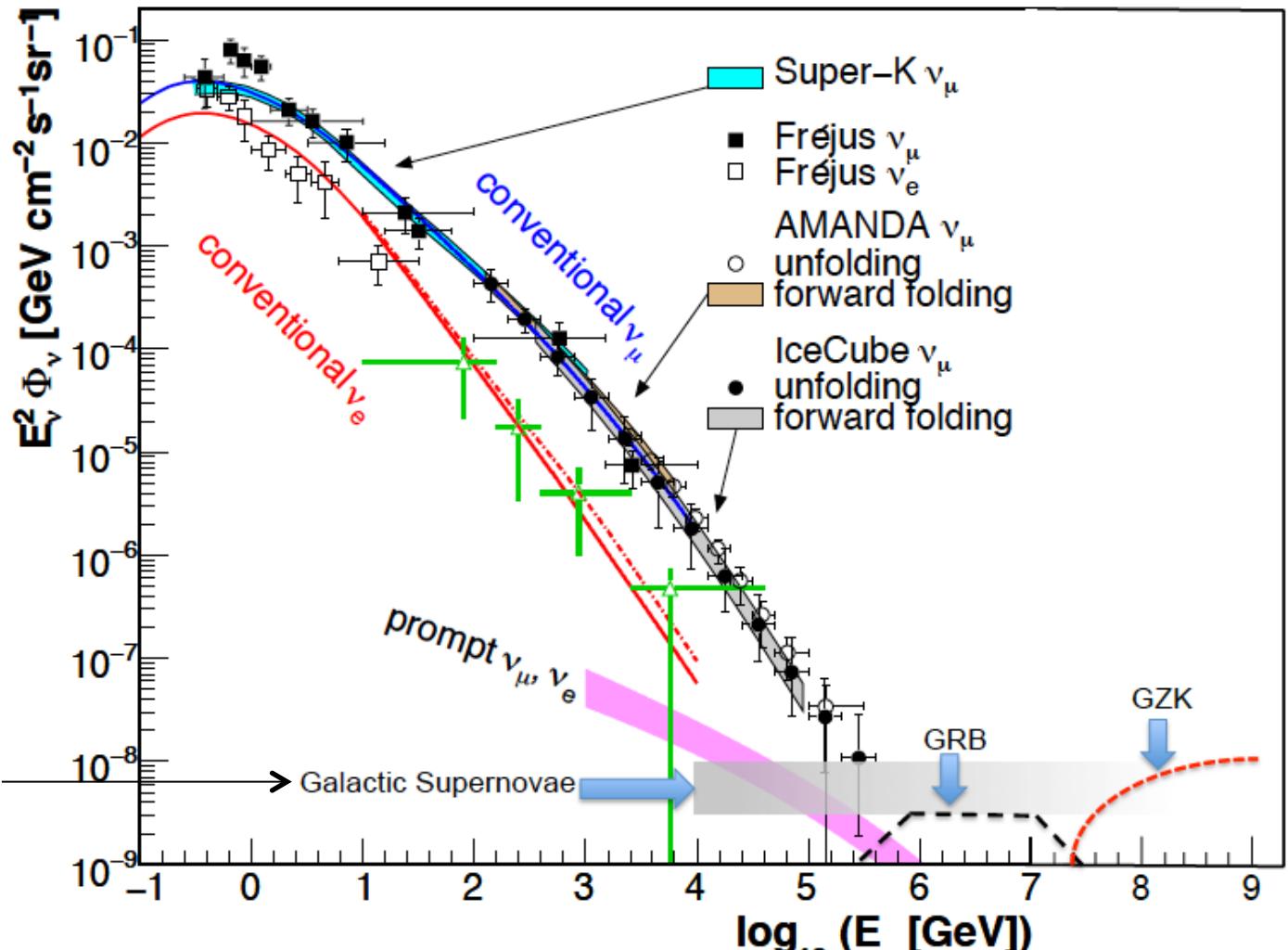
Chandra
Cassiopeia A



gamma
ray
bursts

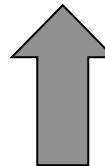
- cosmic neutrinos: energy > 100 TeV
- atmospheric background: 1~2 events per year

$$dN/dE \sim E^{-2}$$

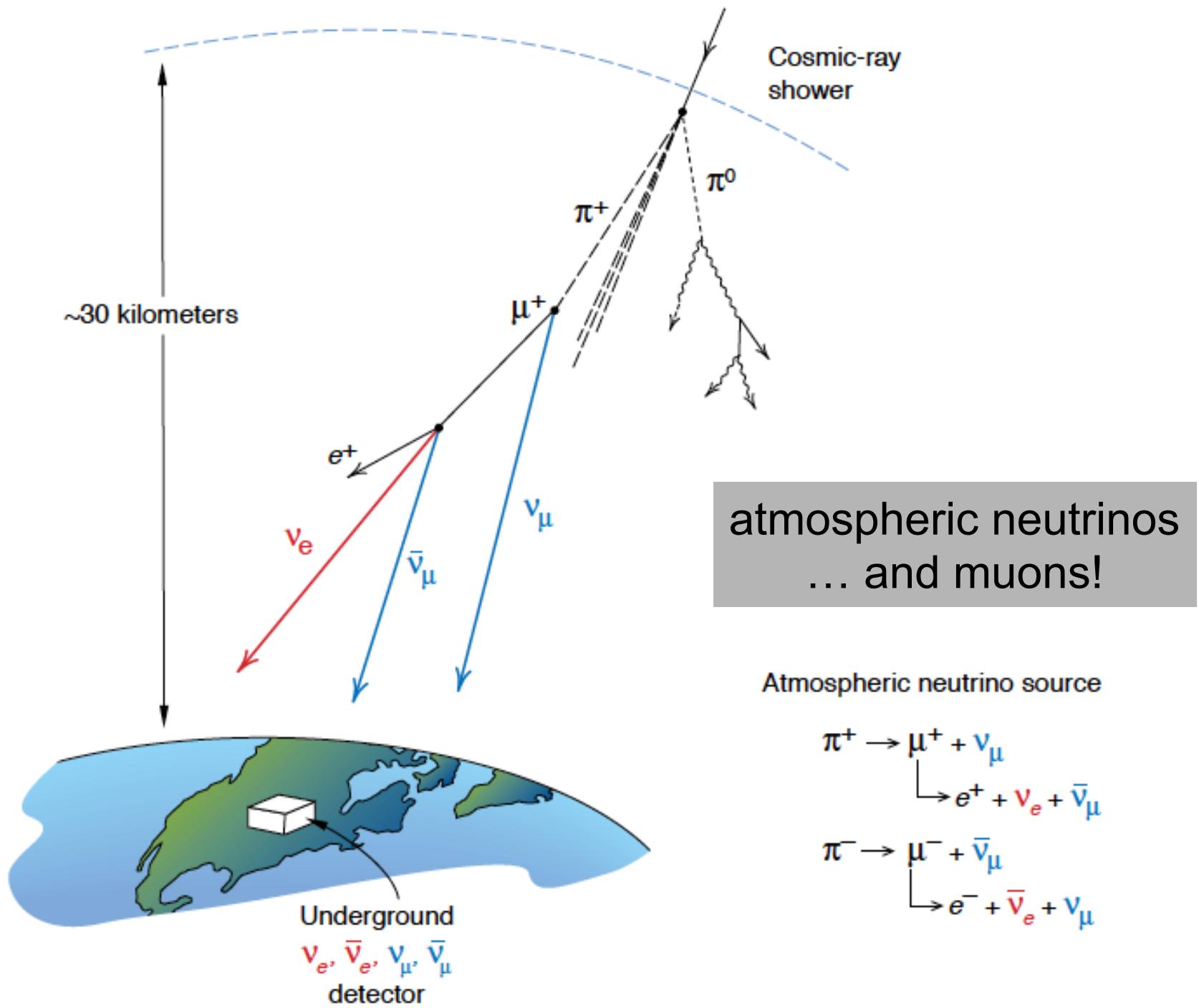


atmospheric

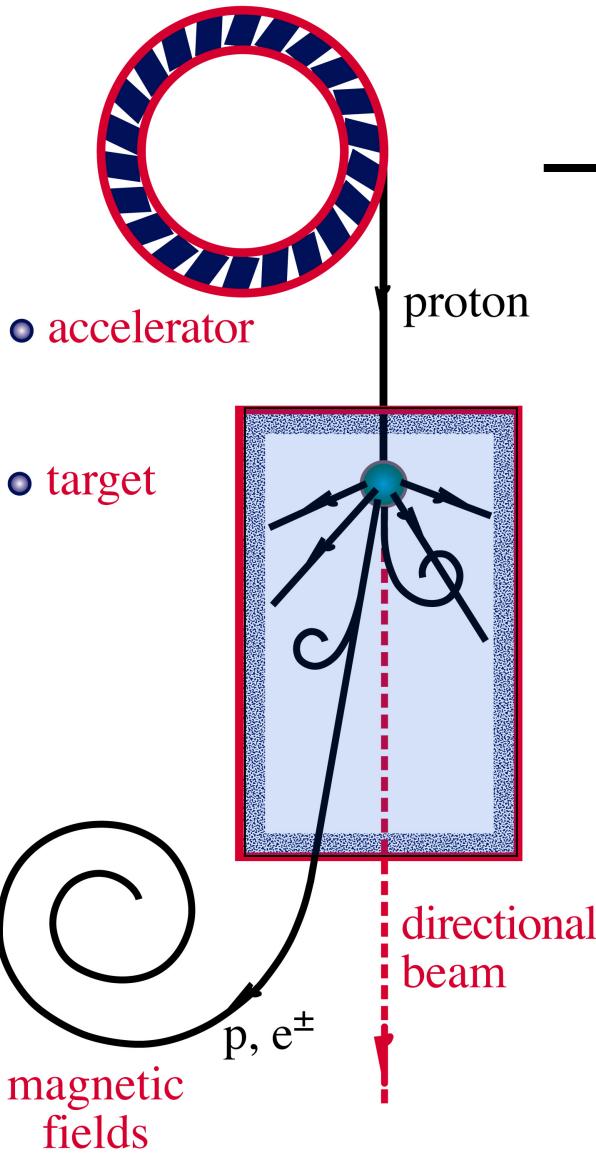
100 TeV



cosmic



ν and γ beams : heaven and earth



accelerator is powered by
large gravitational energy

**black hole
neutron star**

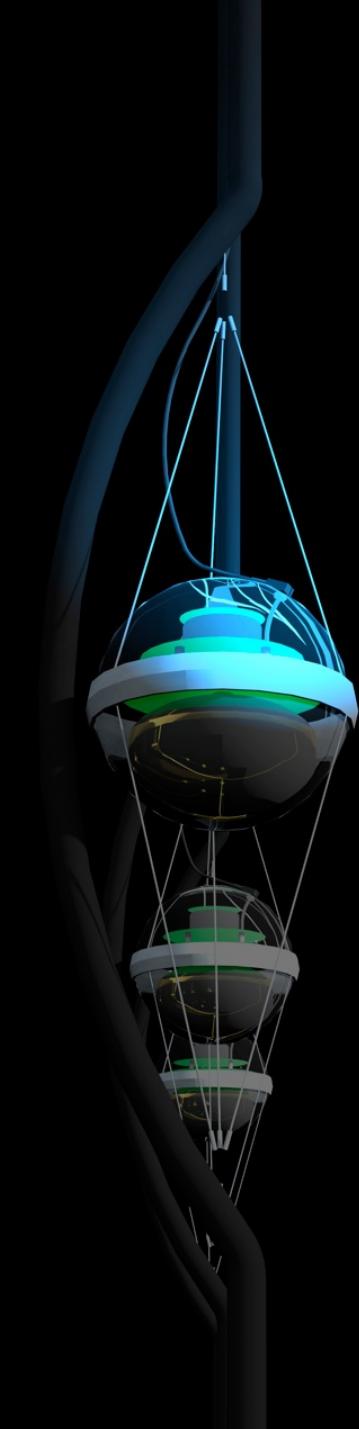
**radiation
and dust**



\sim cosmic ray + neutrino



\sim cosmic ray + gamma



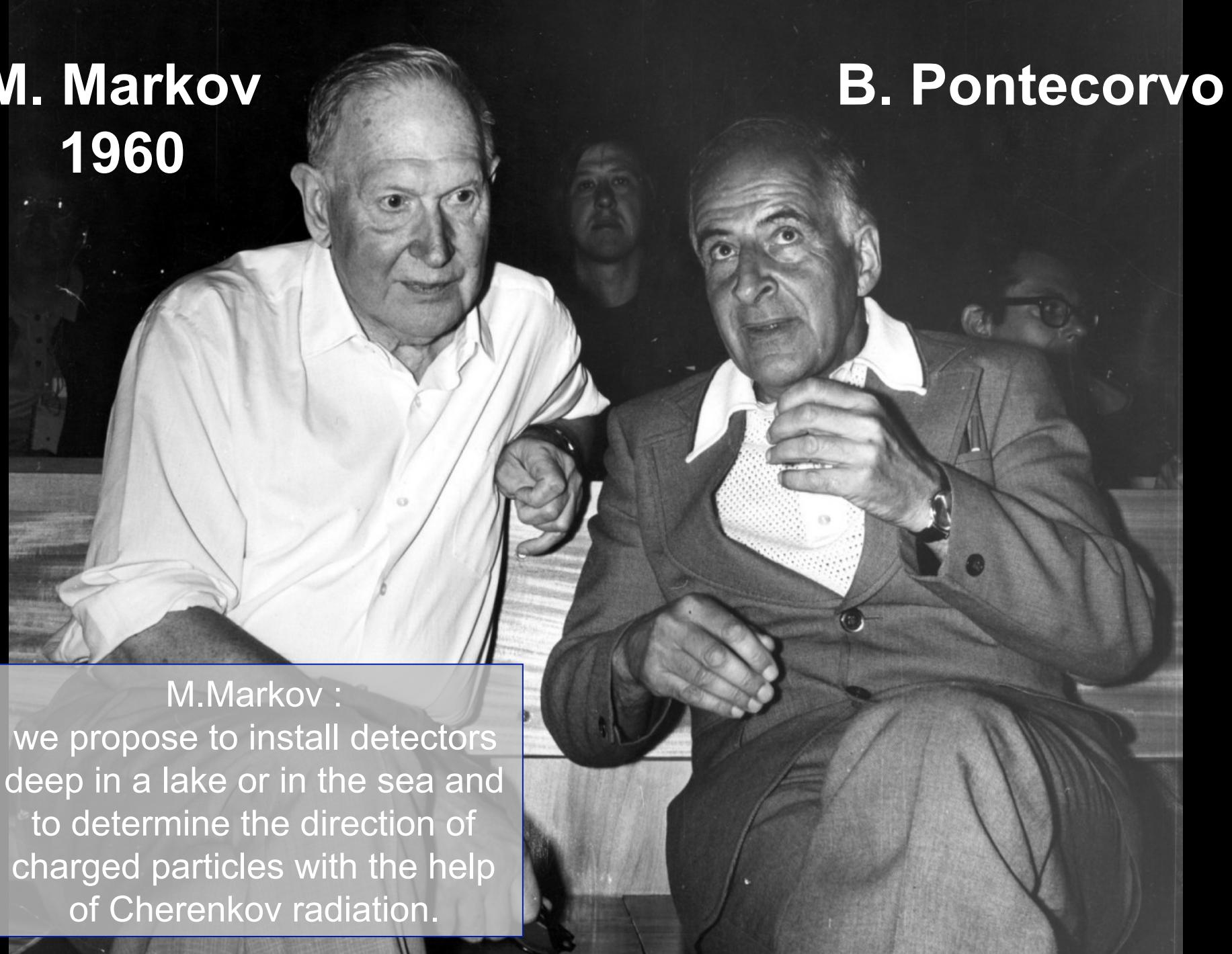
IceCube: the discovery of cosmic neutrinos

francis halzen

- cosmic ray accelerators
- IceCube: a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

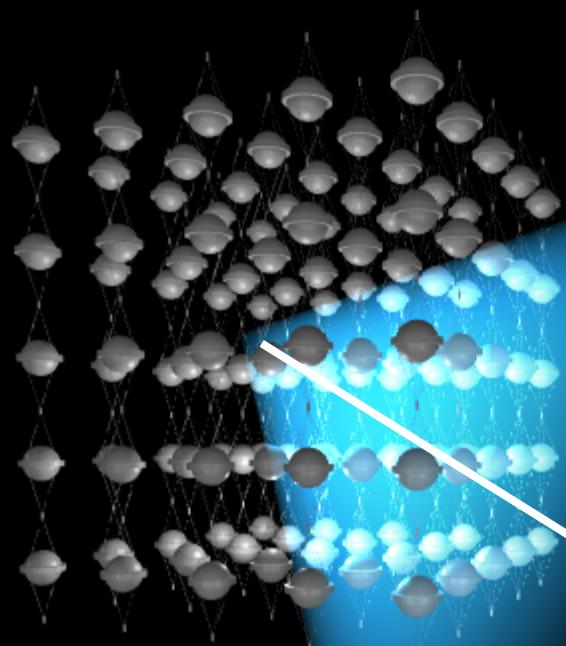
M. Markov
1960

B. Pontecorvo

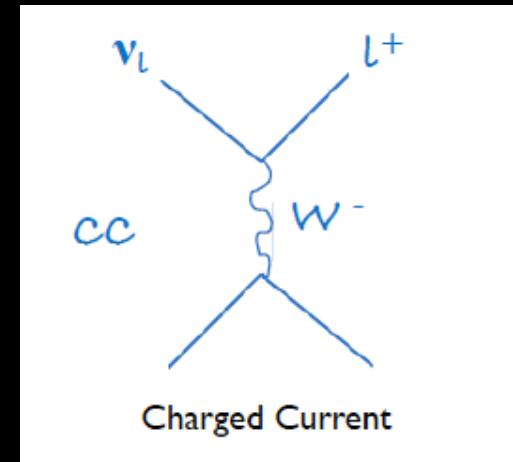


M. Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.

- shielded and optically transparent medium

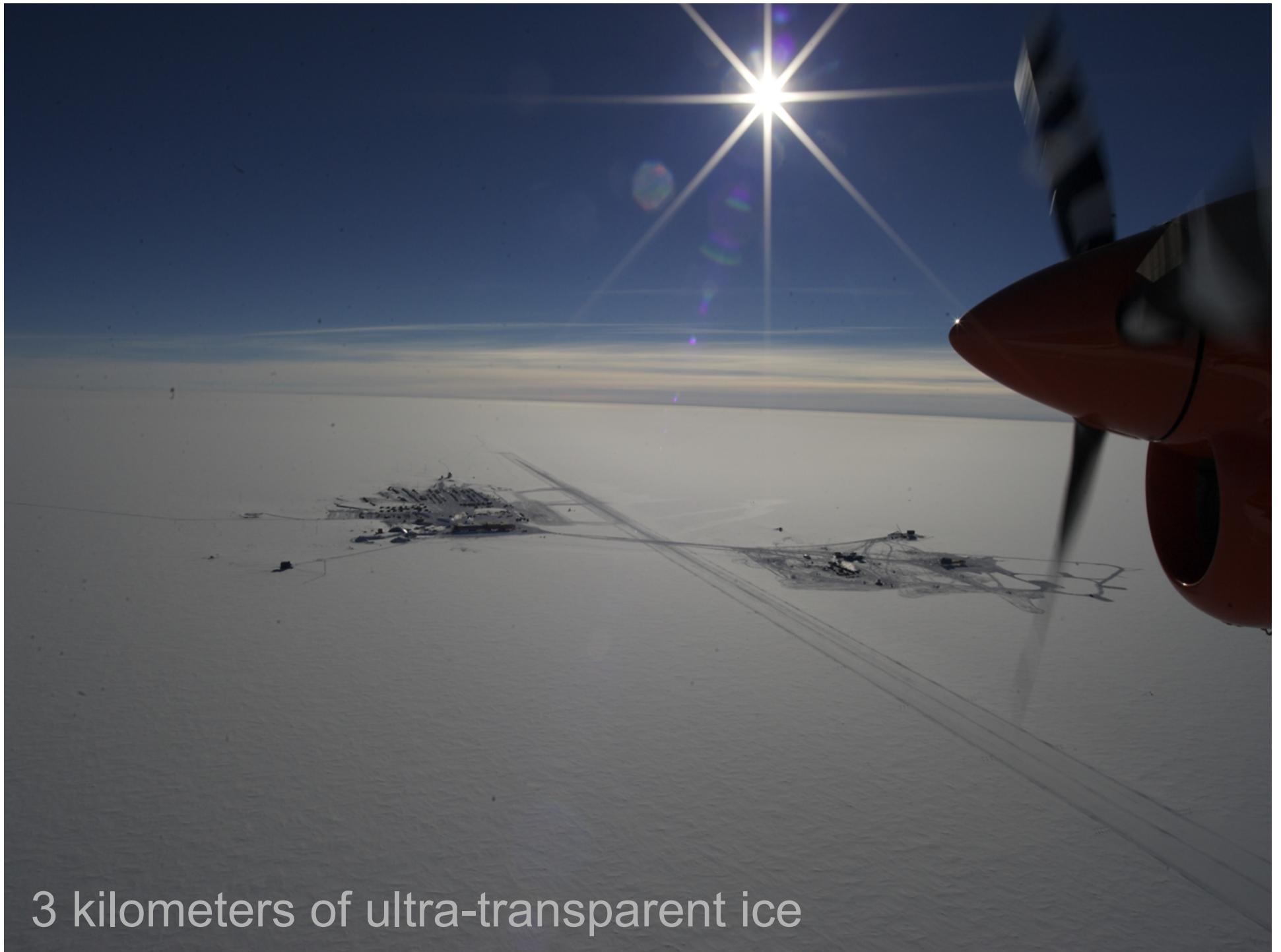


μ



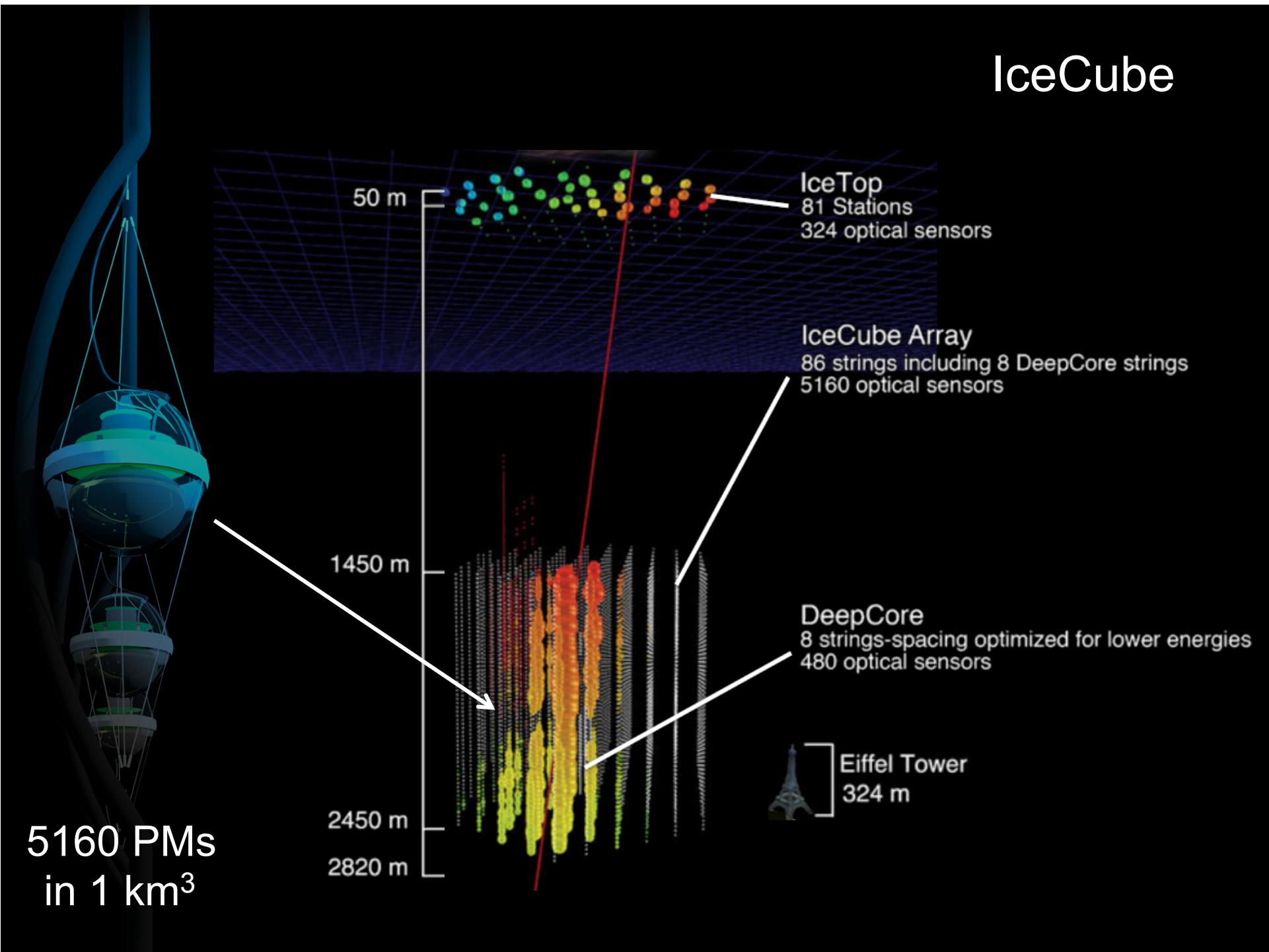
ν

- lattice of photomultipliers



3 kilometers of ultra-transparent ice

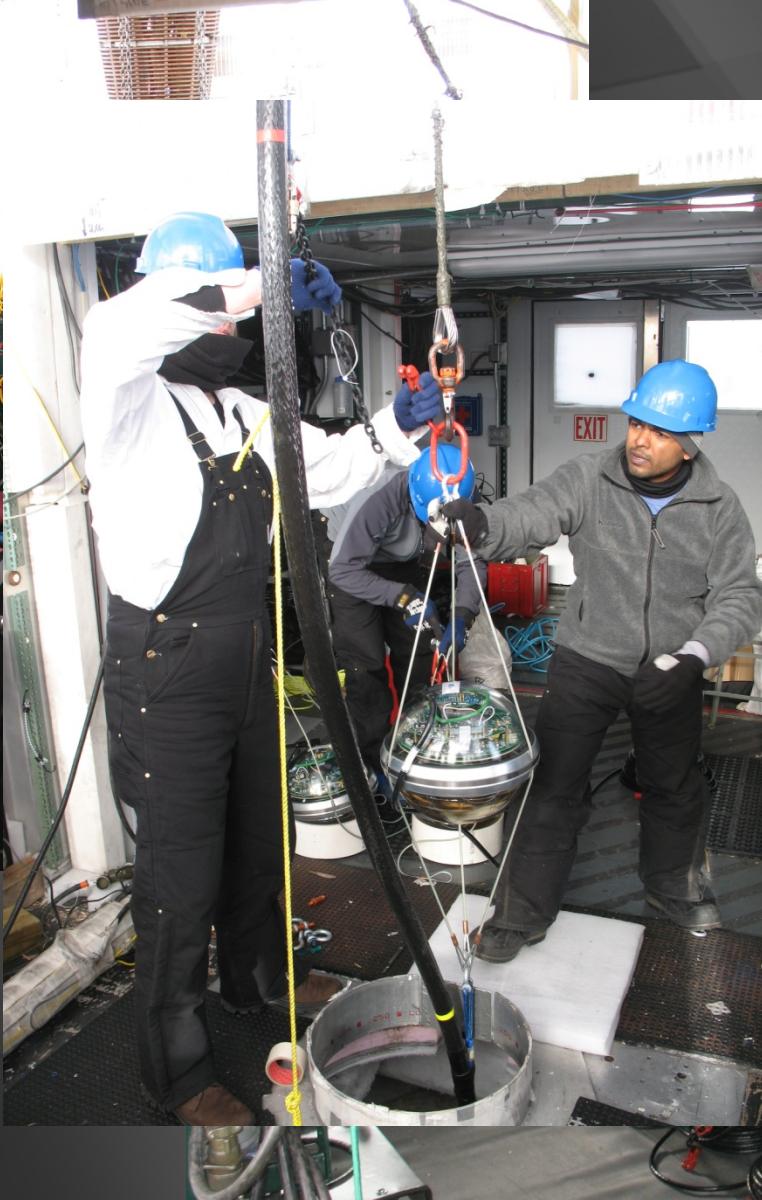
IceCube



photomultiplier
tube -10 inch

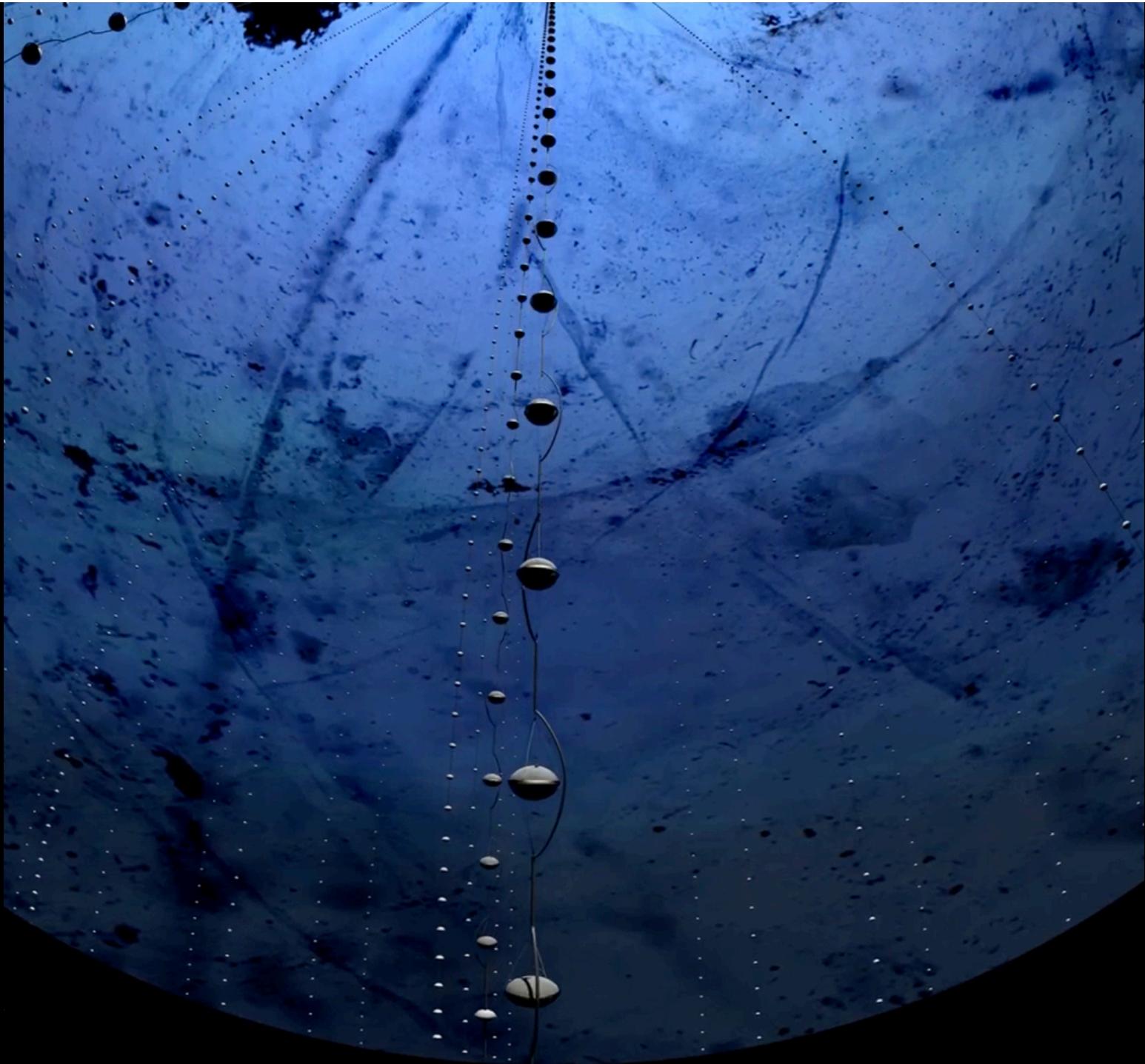


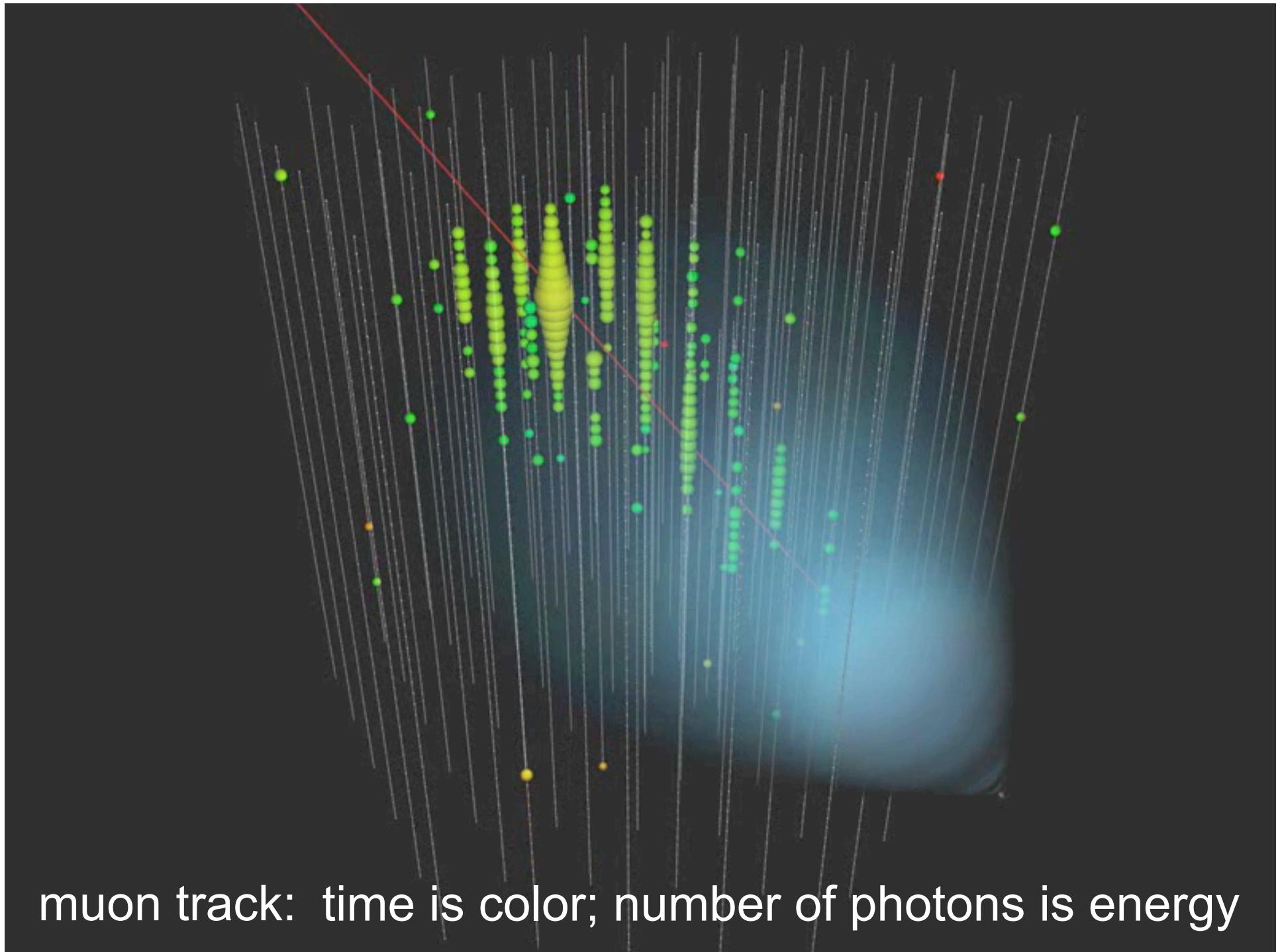
drilling and deployment



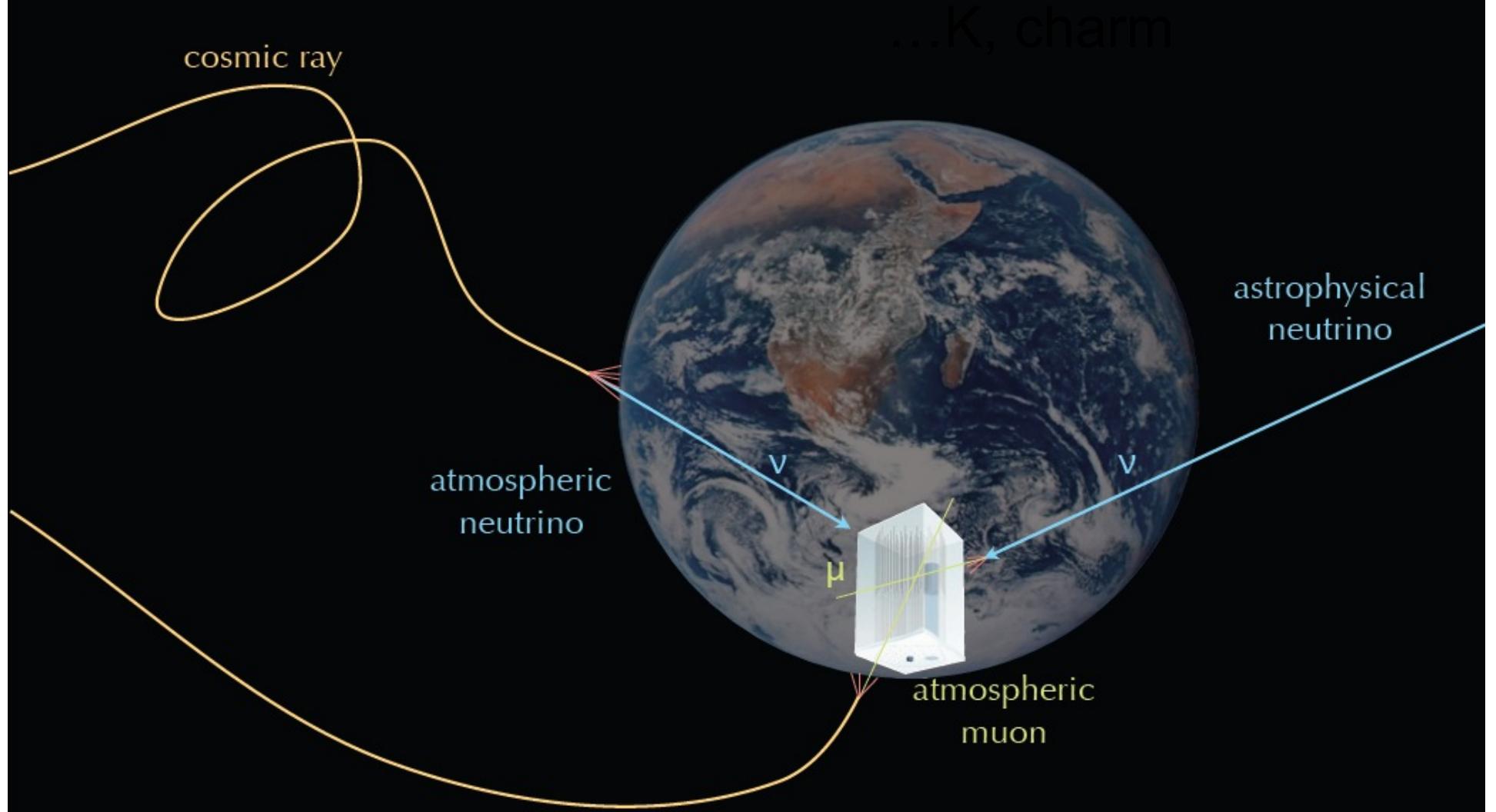
2 days per hole
3.5 cm/second

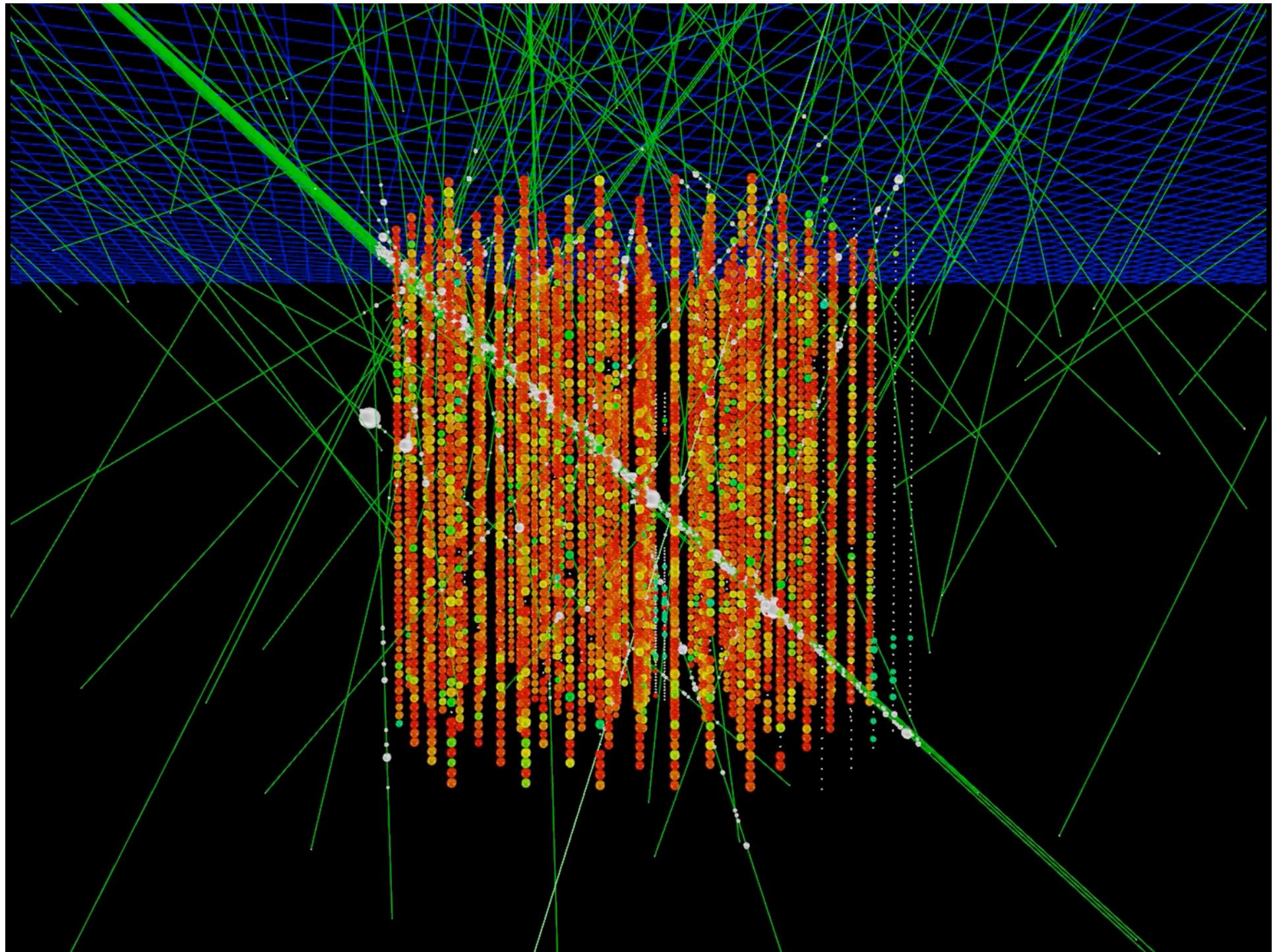






Signals and Backgrounds





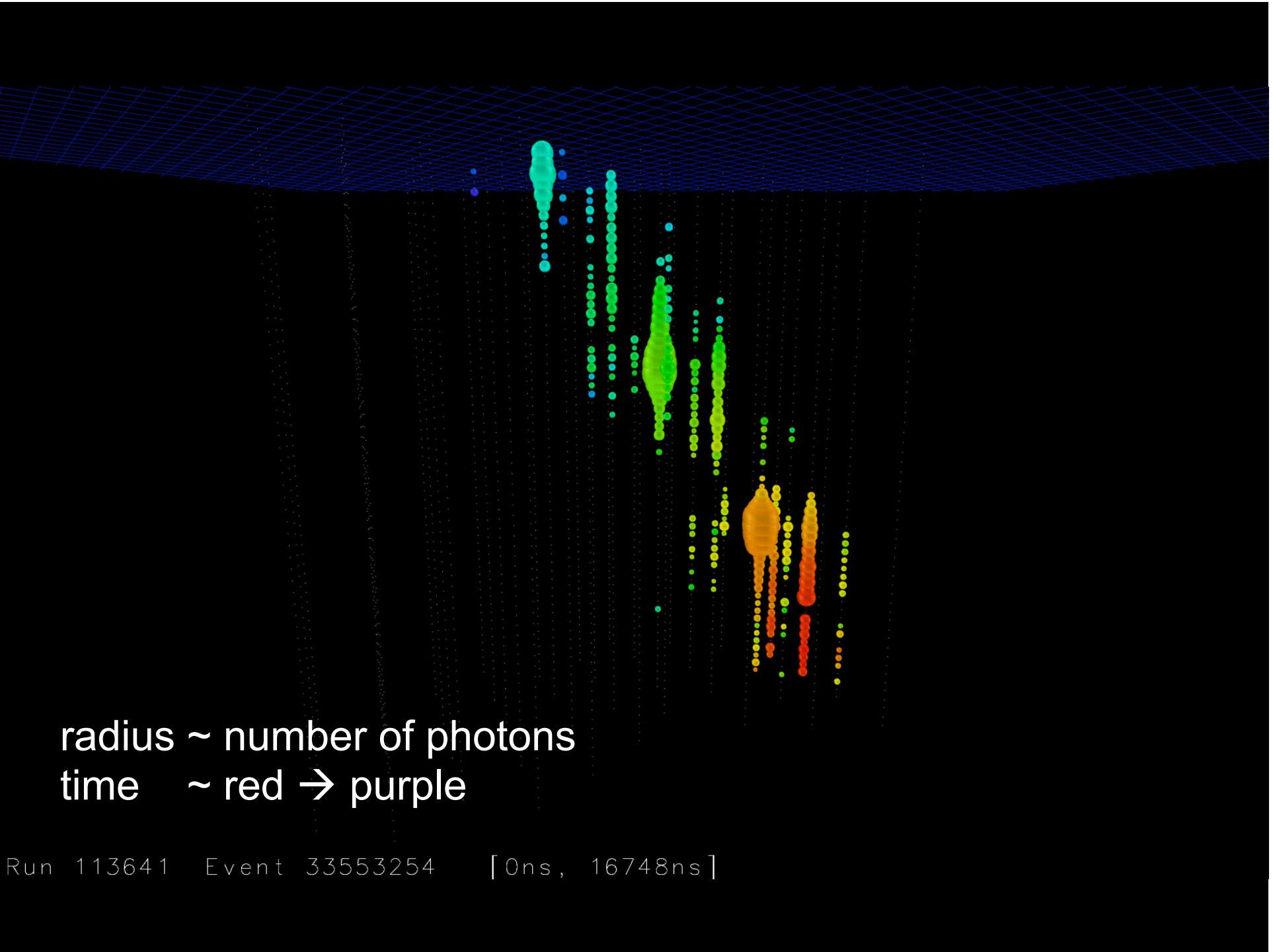
... you looked at 10msec of data !

muons detected per year:

- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

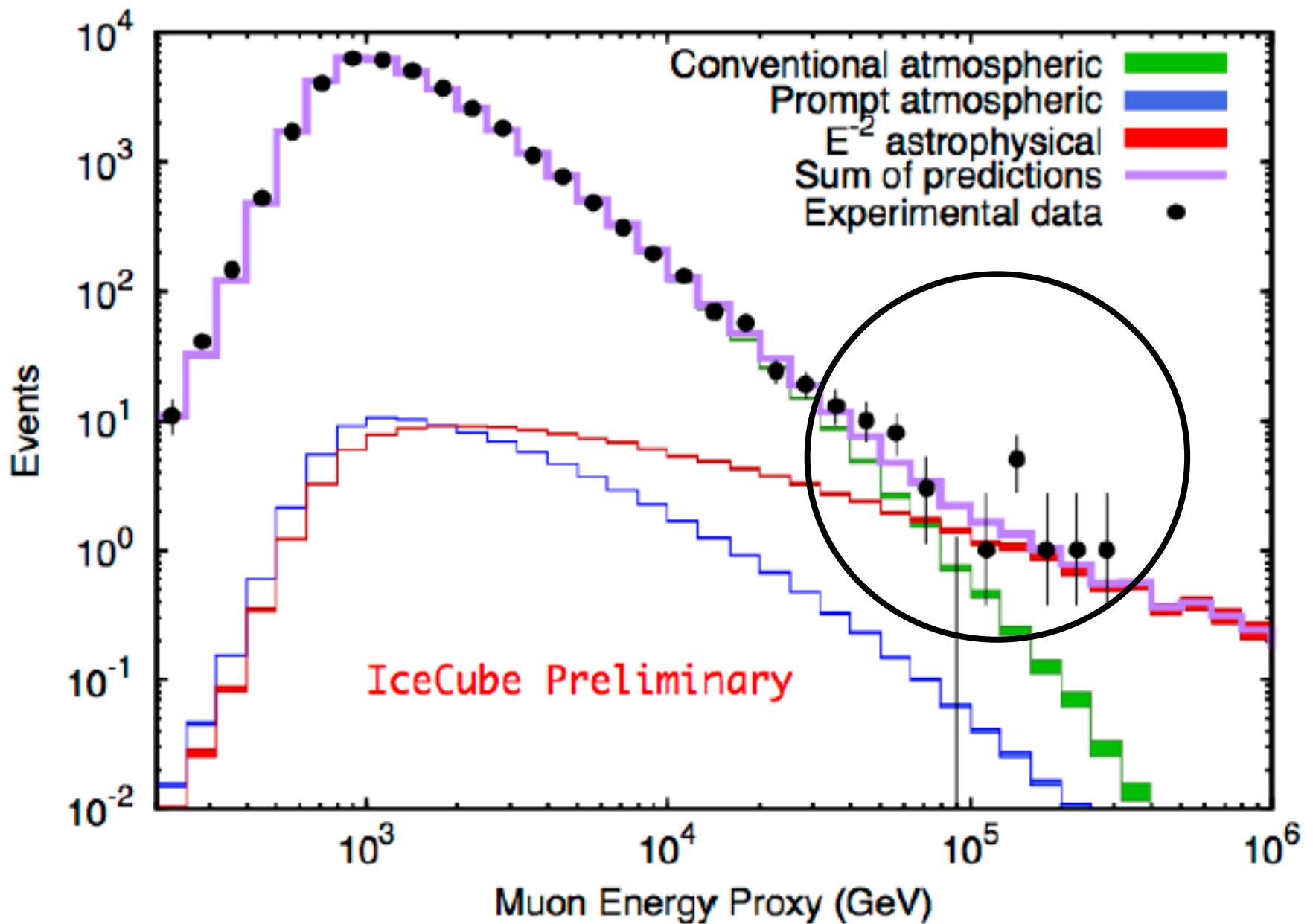
** 1 every 6 minutes



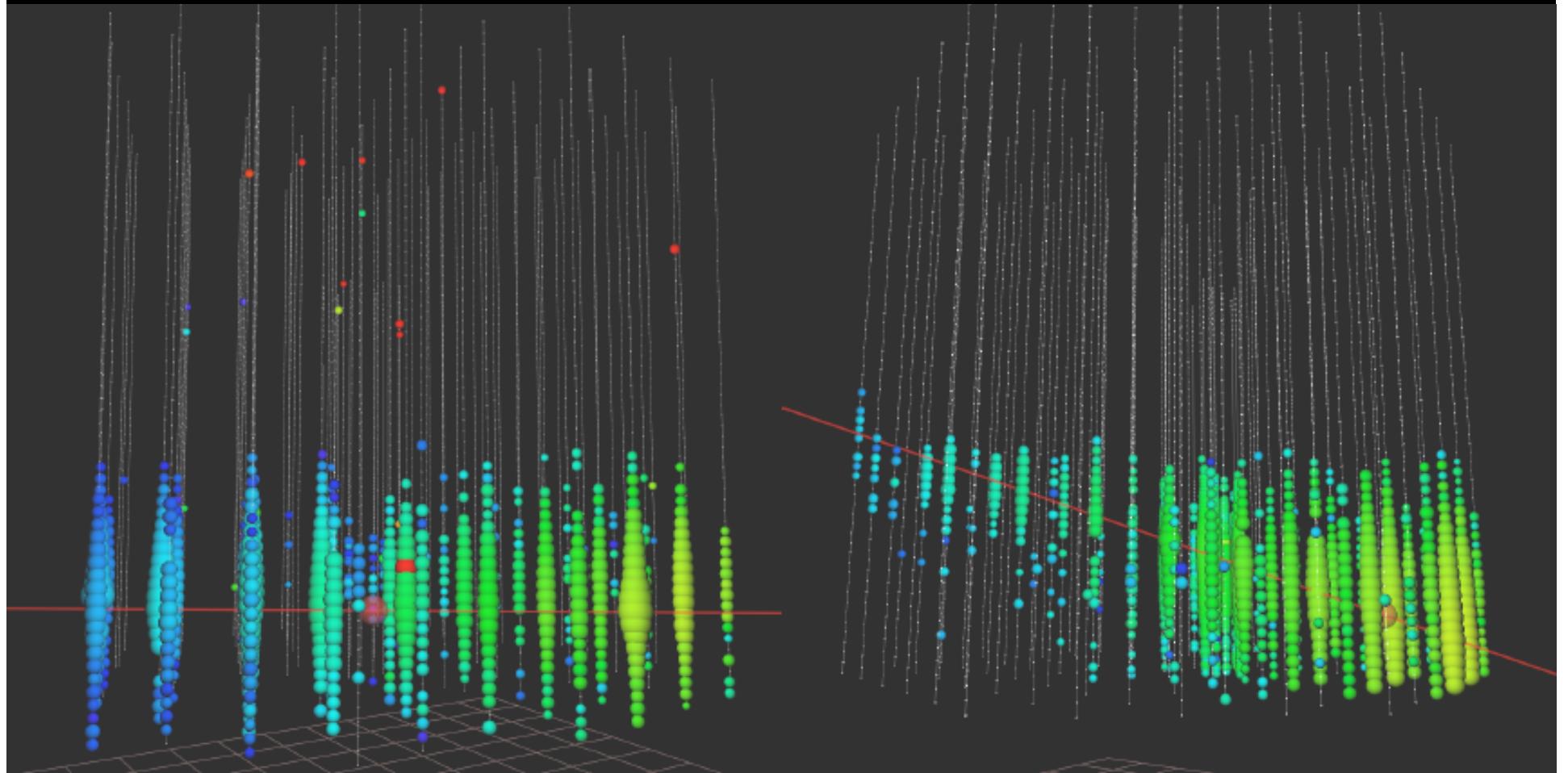
radius ~ number of photons
time ~ red → purple

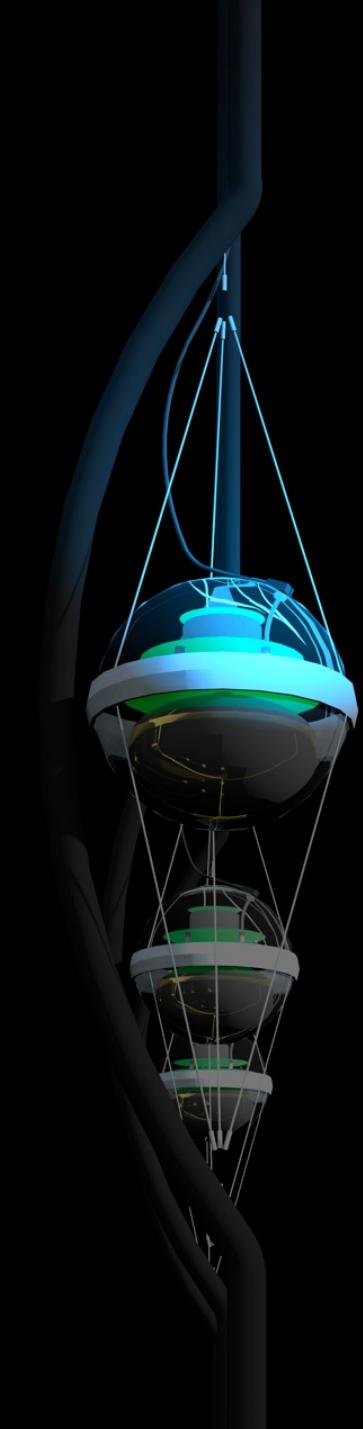
Run 113641 Event 33553254 [0ns, 16748ns]

cosmic neutrinos in 2 years of data at 3.7 sigma



highest energy muon energy observed: 560 TeV
→ PeV energy neutrino



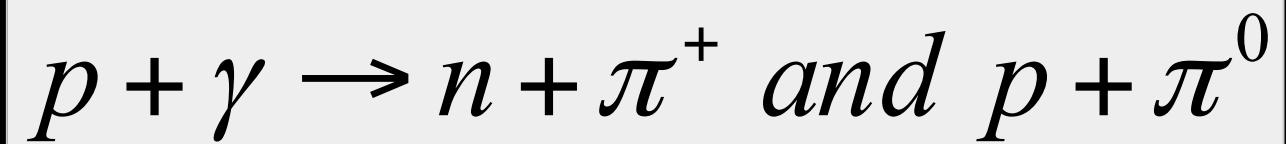


IceCube: the discovery of cosmic neutrinos

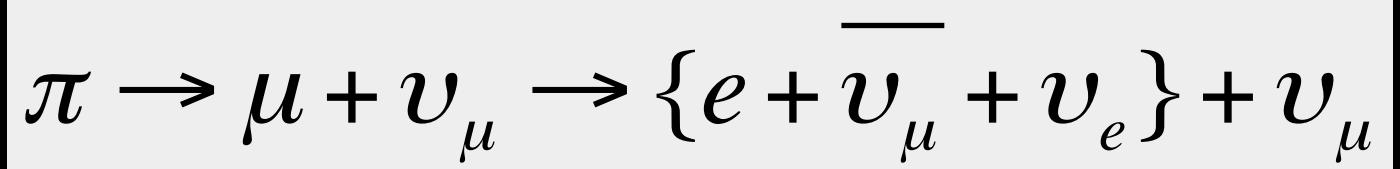
francis halzen

- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

cosmic rays interact with the microwave background

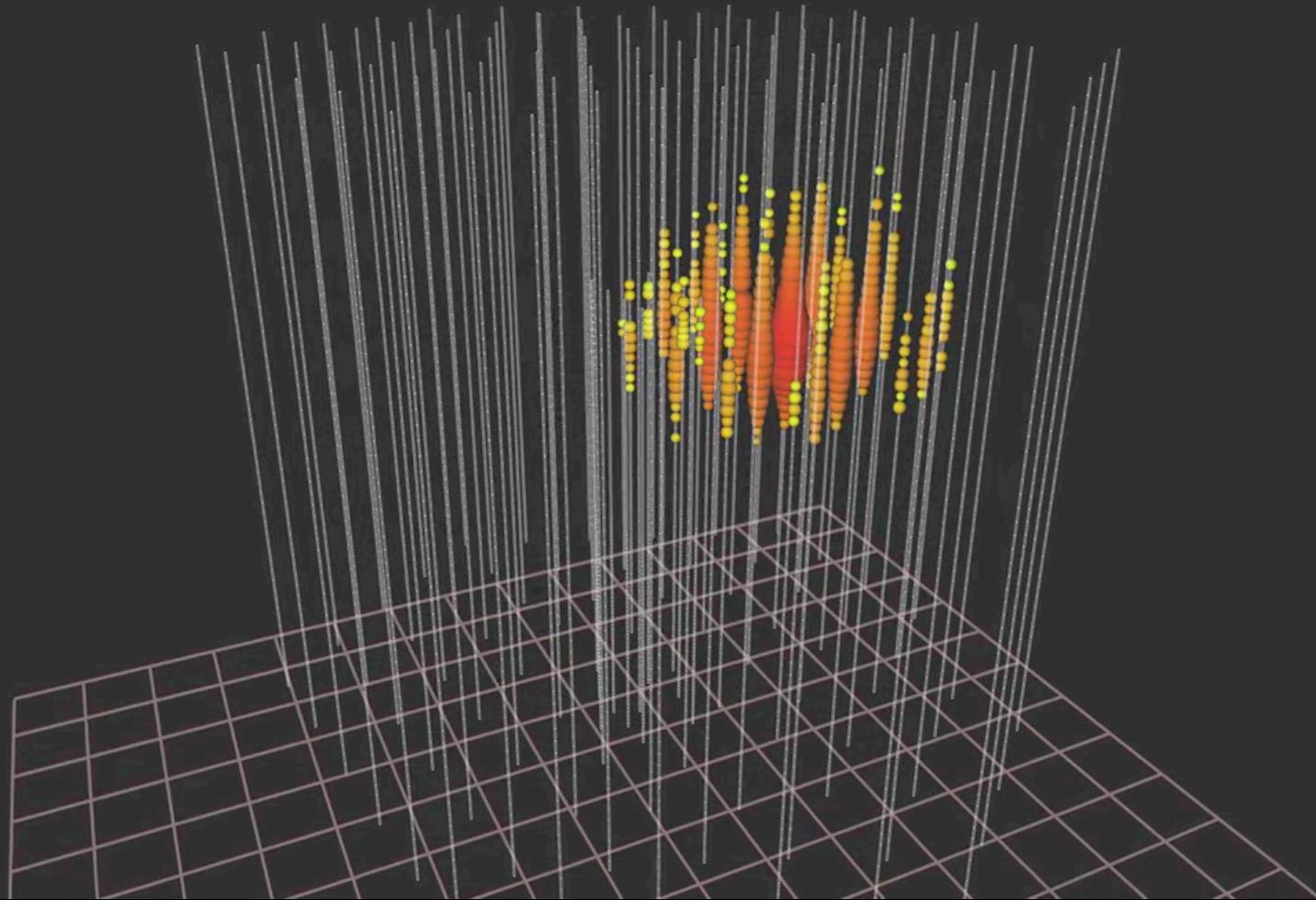


cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

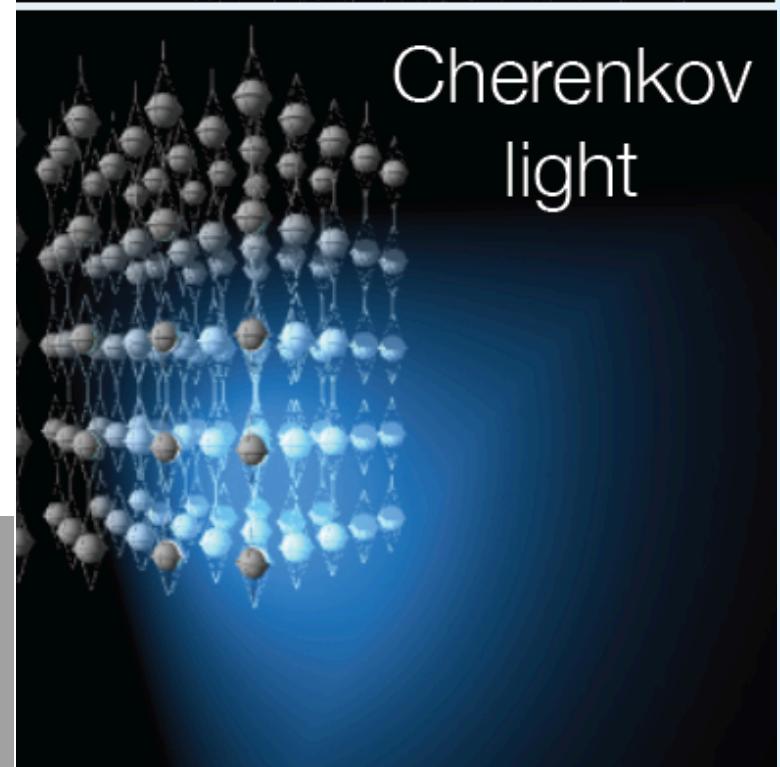
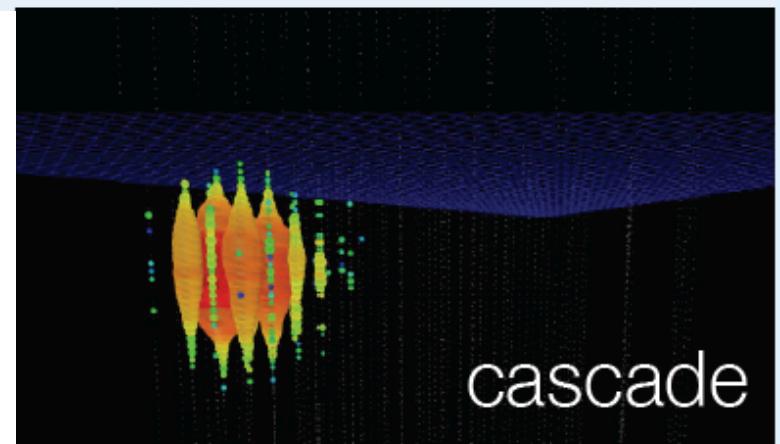
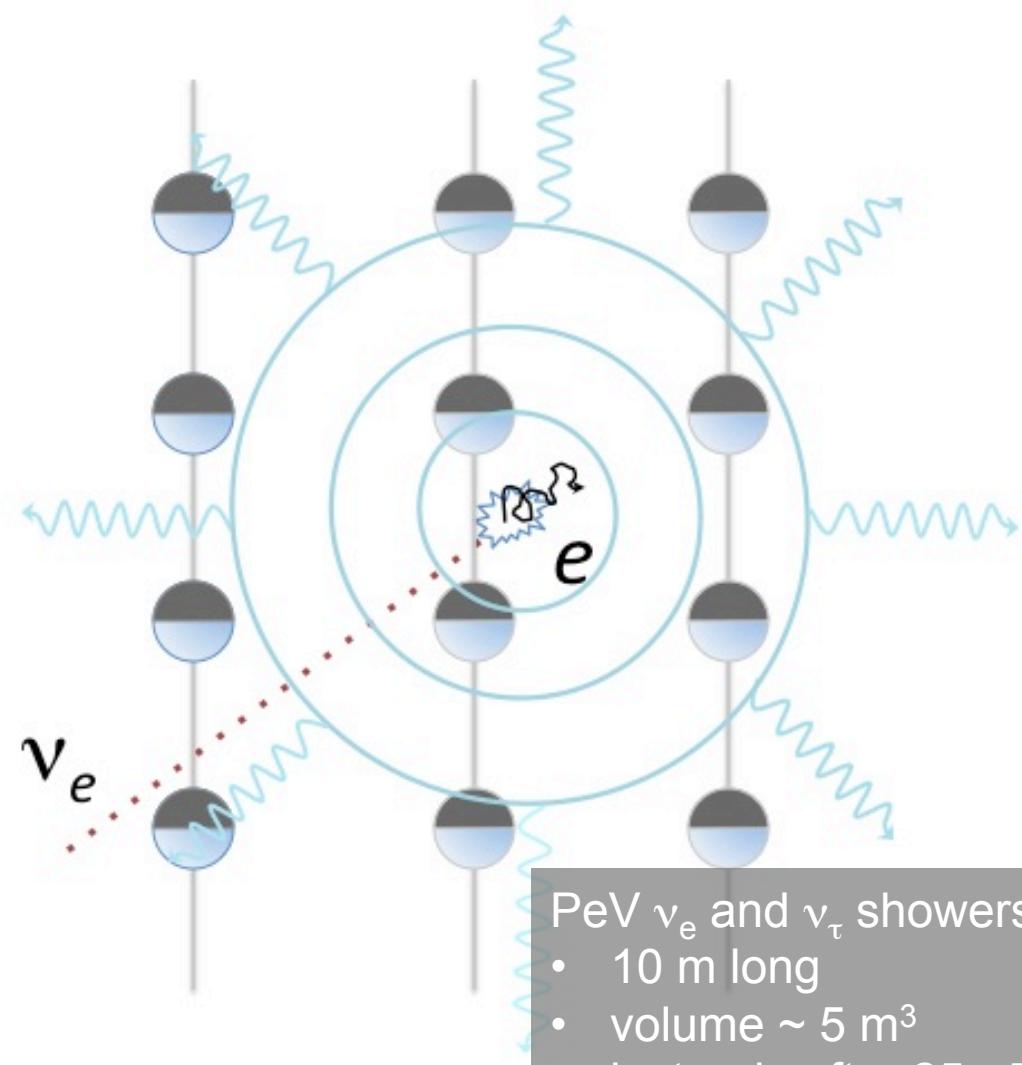


1 event per cubic kilometer per year
...but it points at its source!

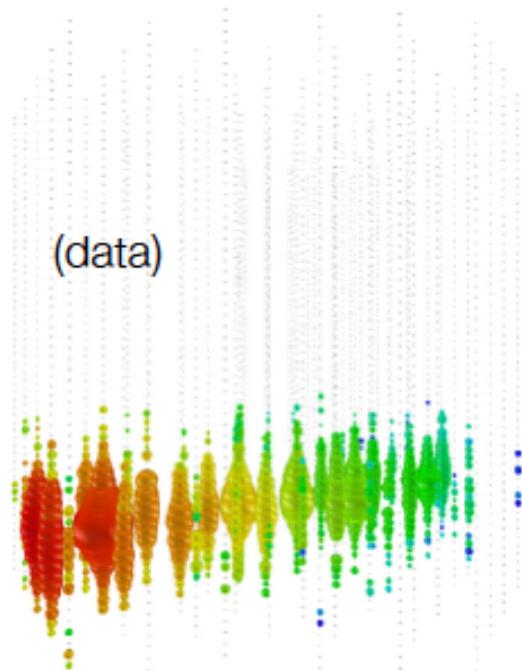
GZK neutrino search: two neutrinos with > 1,000 TeV



tracks and showers



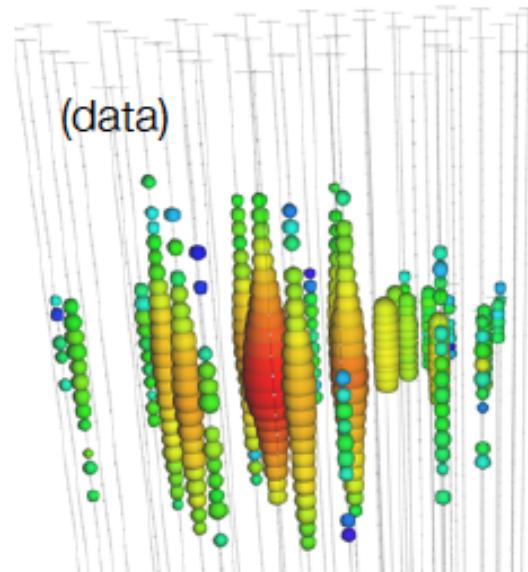
Charged-current ν_μ



Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

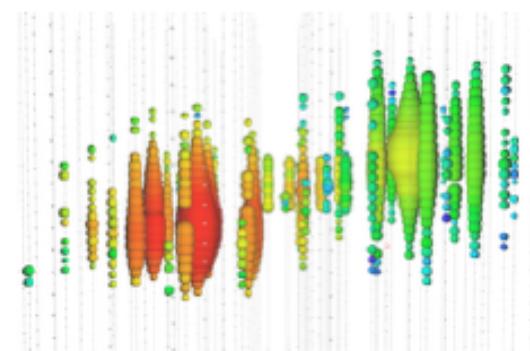
Neutral-current / ν_e



**Isolated energy deposition (cascade)
with no track**

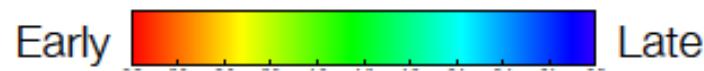
15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

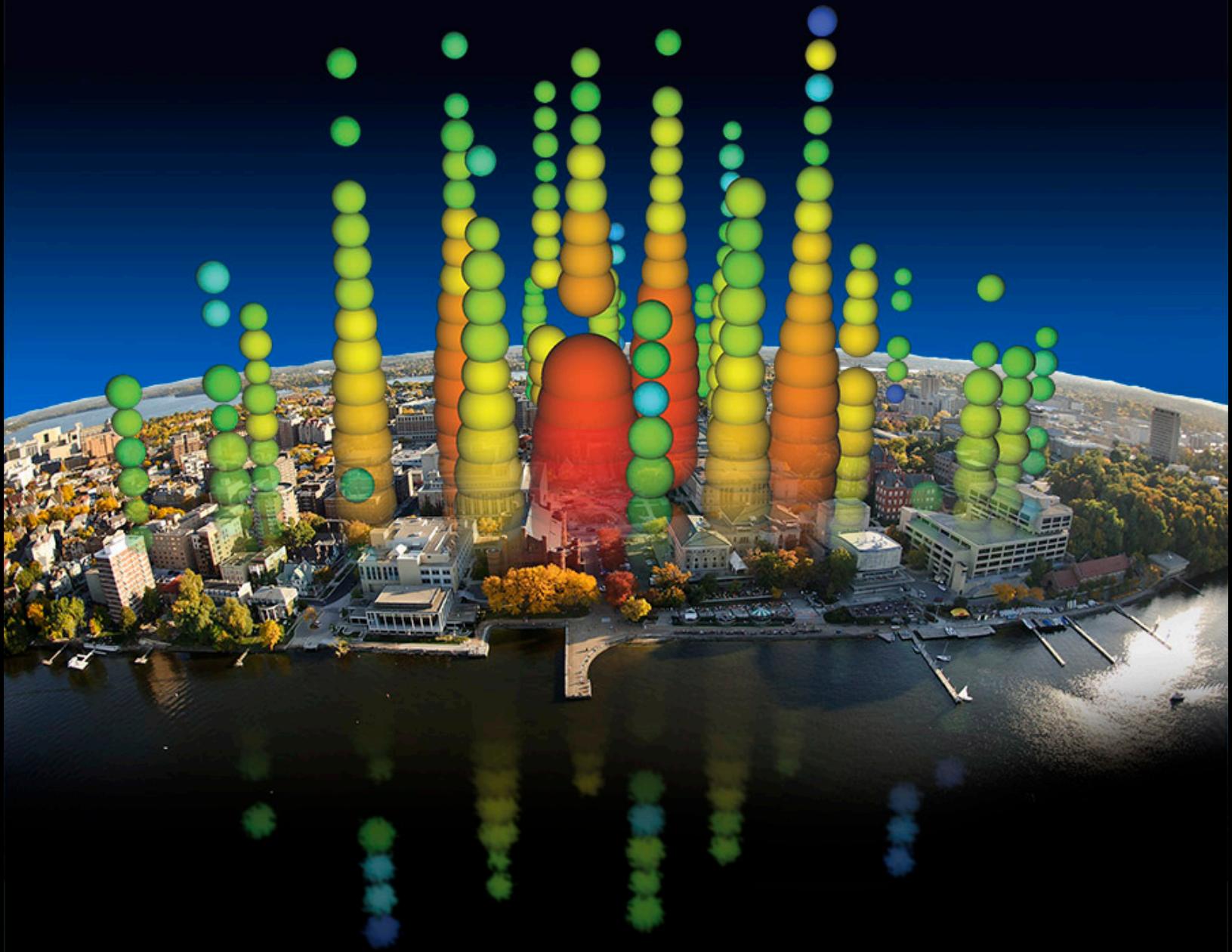
Charged-current ν_τ



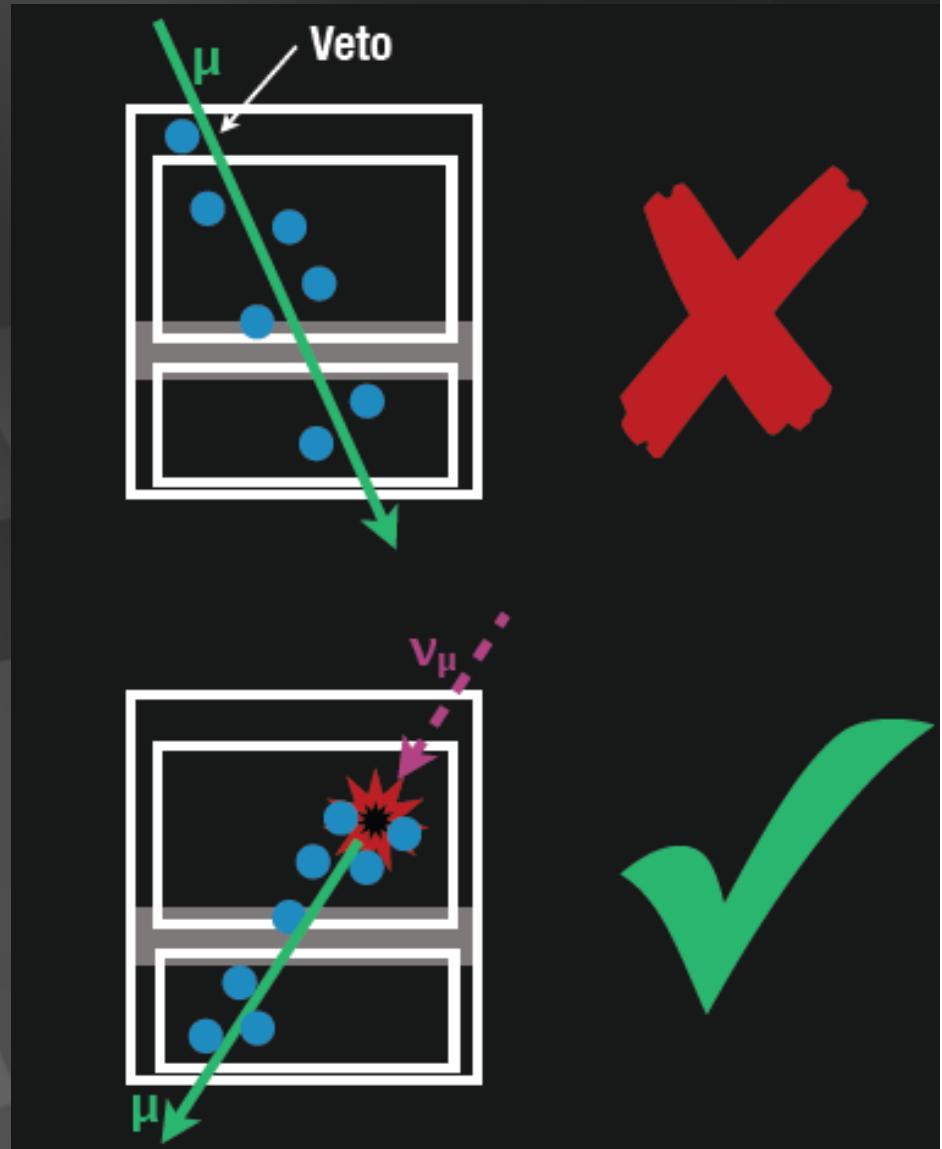
"Double-bang"

(none observed yet: τ decay length is 50 m/PeV)



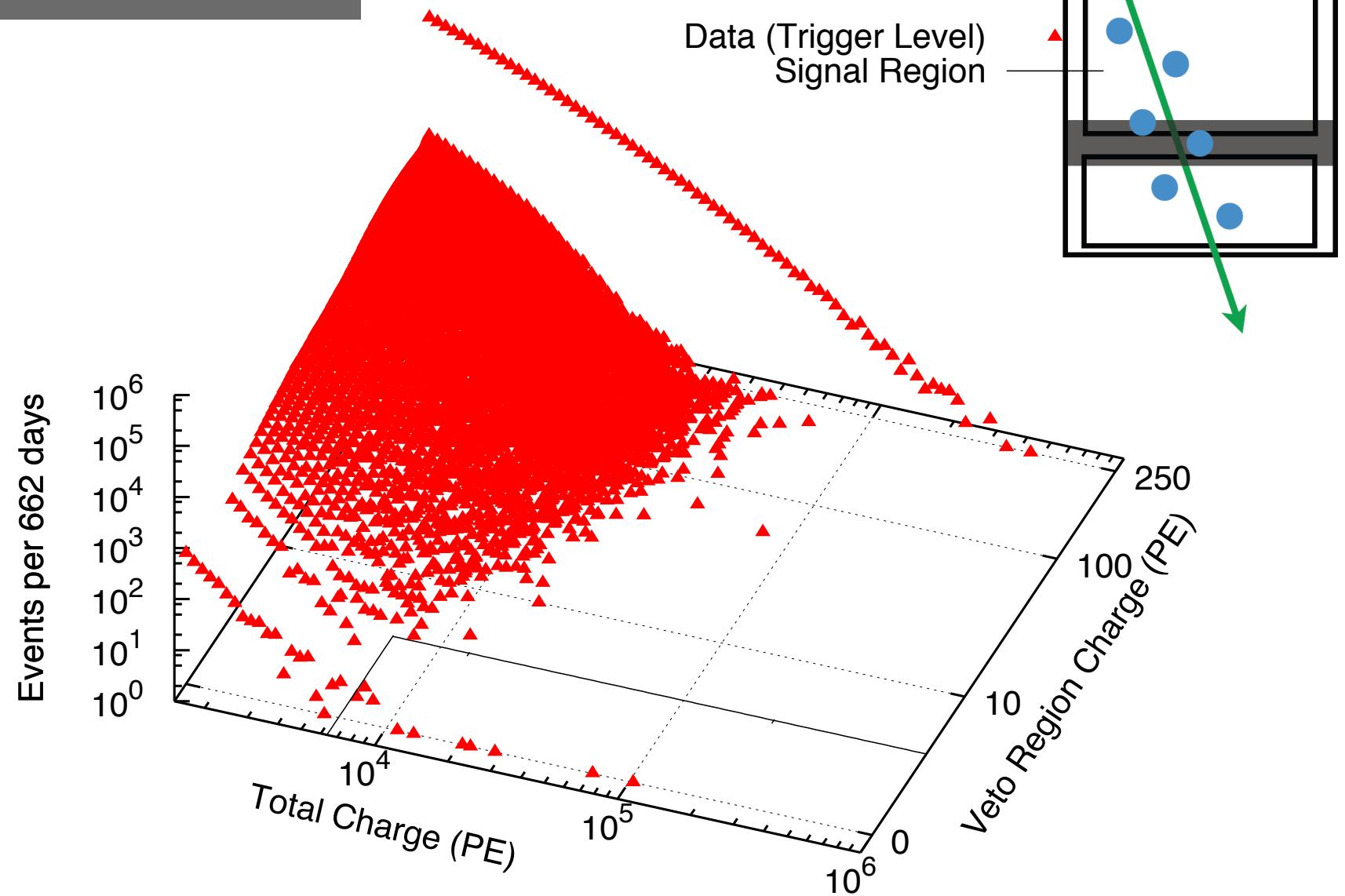


- find contained events (420 Mton)
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution



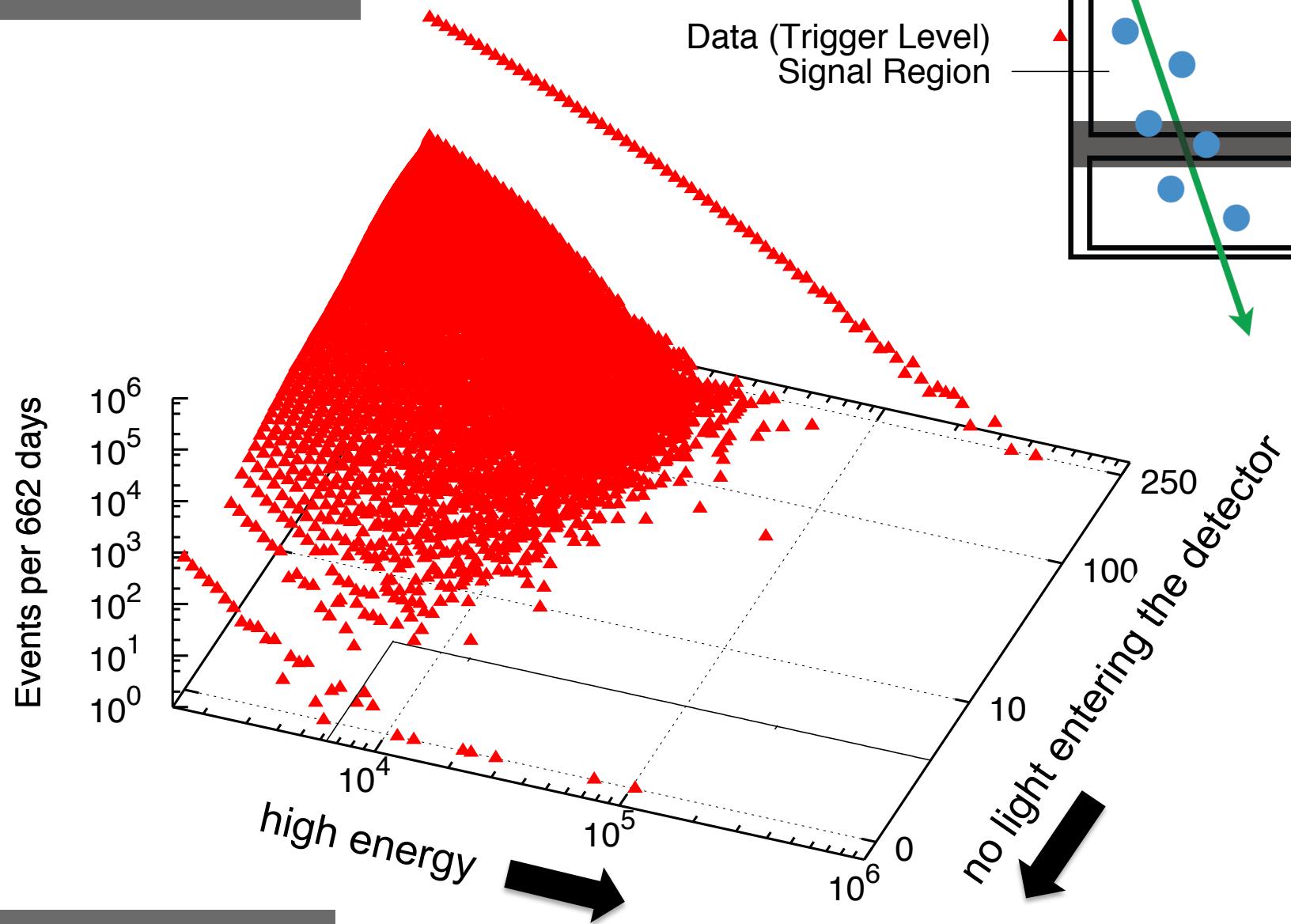
loss in statistics is compensated by event definition

...and then there
were 26 more...



data: 86 strings one year

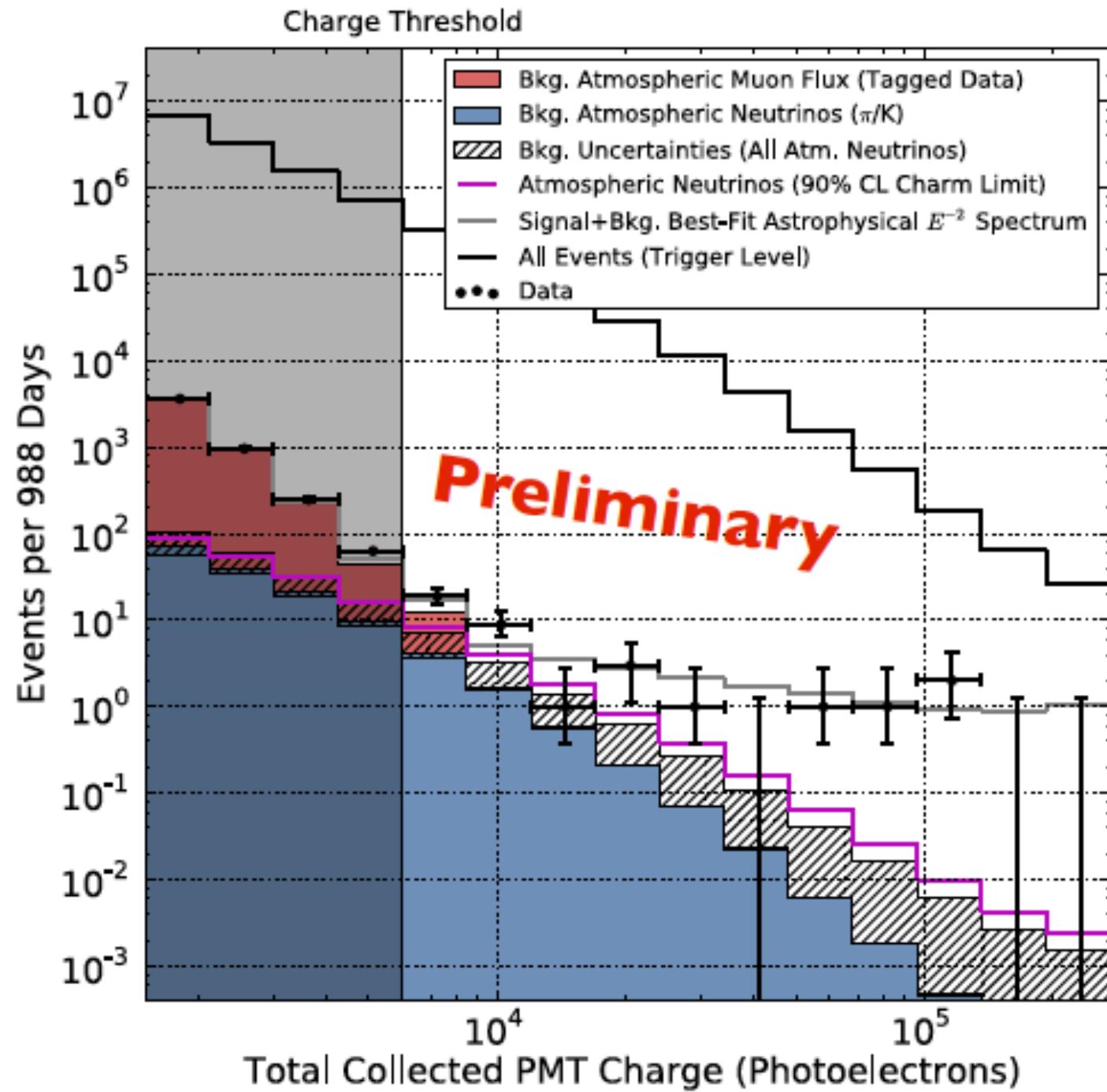
...and then there
were 26 more...



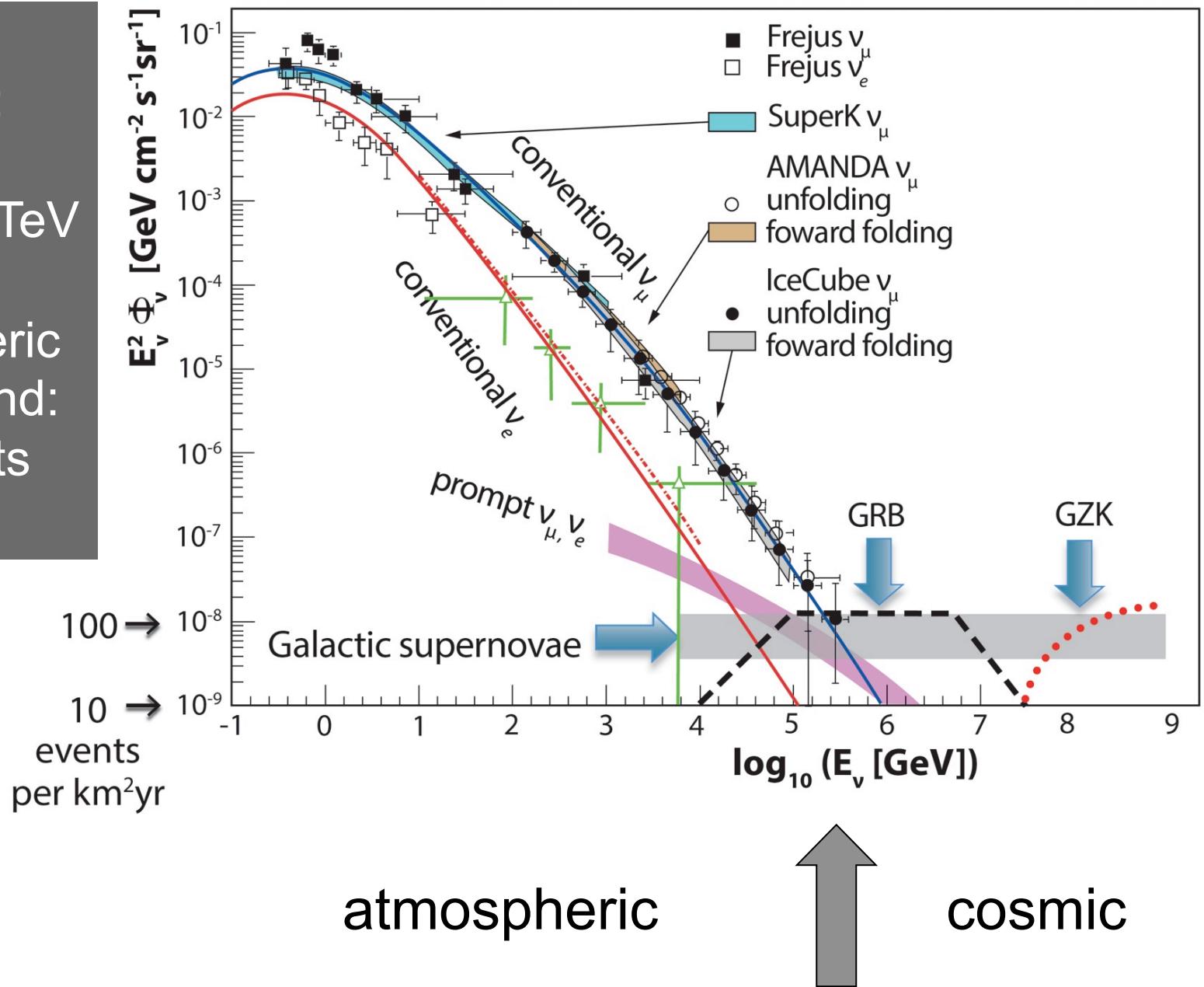
data: 86 strings one year

total charge
collected
by PMTs of
events with
interaction
inside the
detector

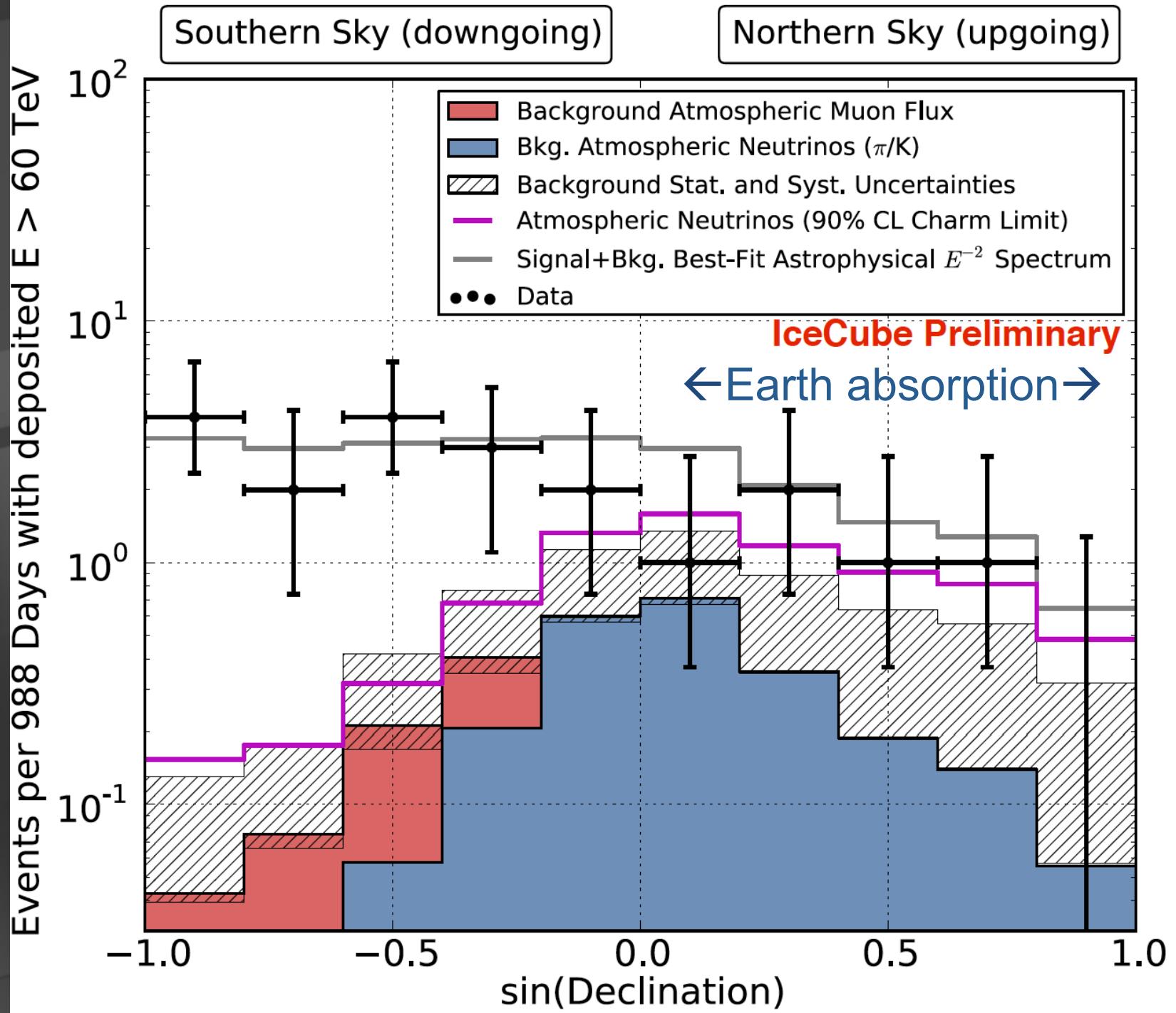
Science 342 (2013)
1242856

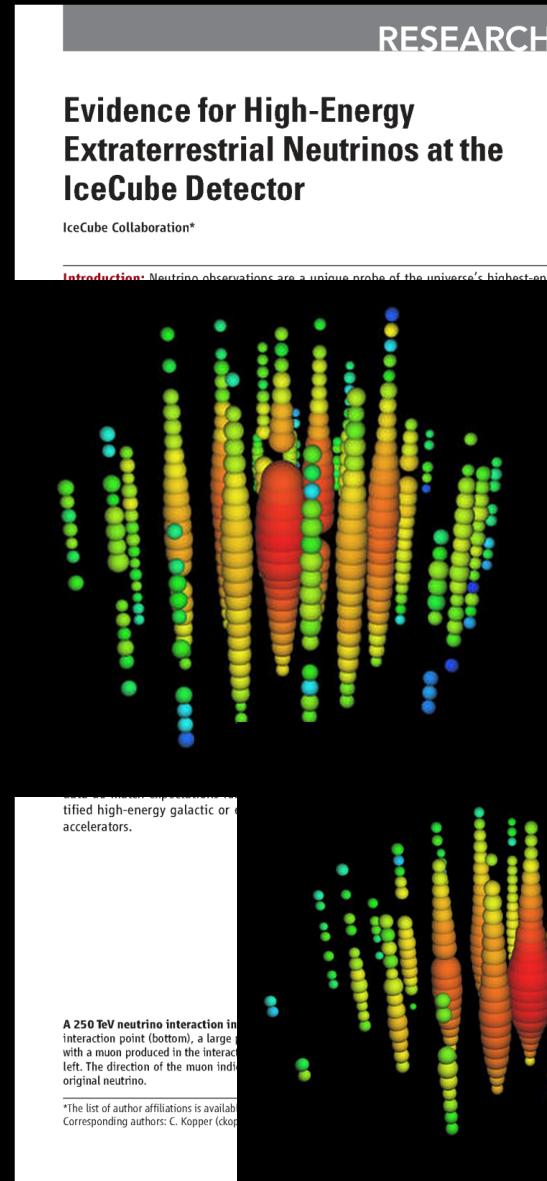


- cosmic neutrinos: energy > 100 TeV
- atmospheric background: 1~2 events per year

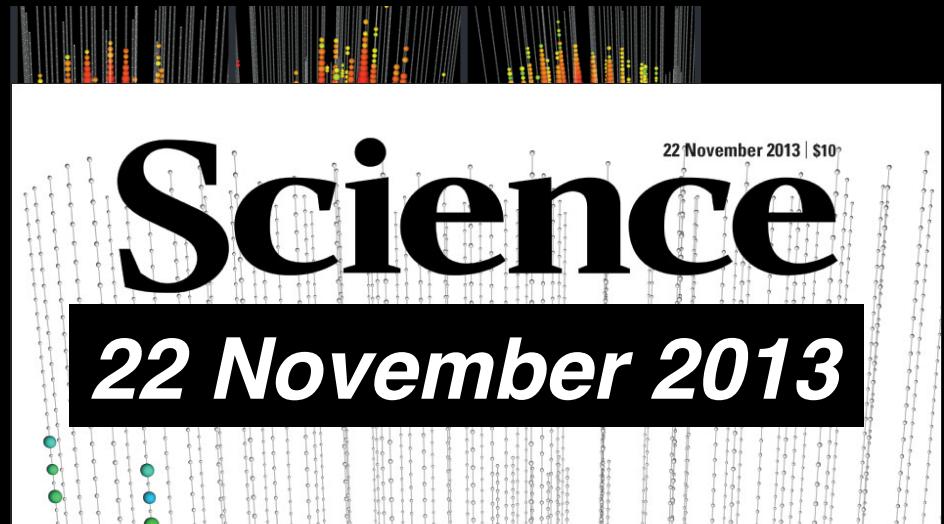
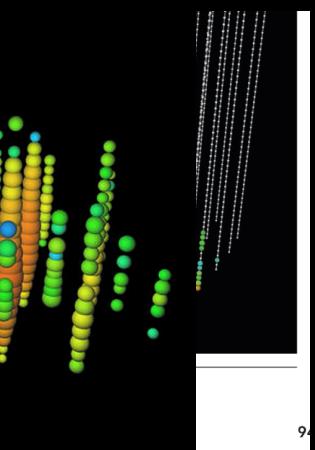
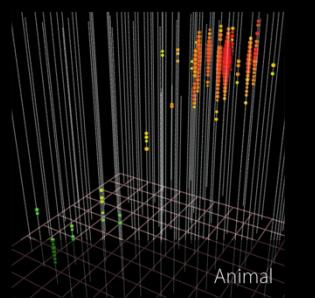
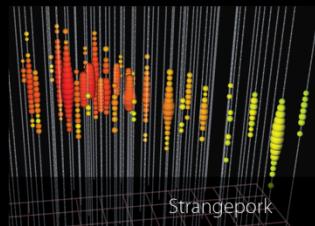


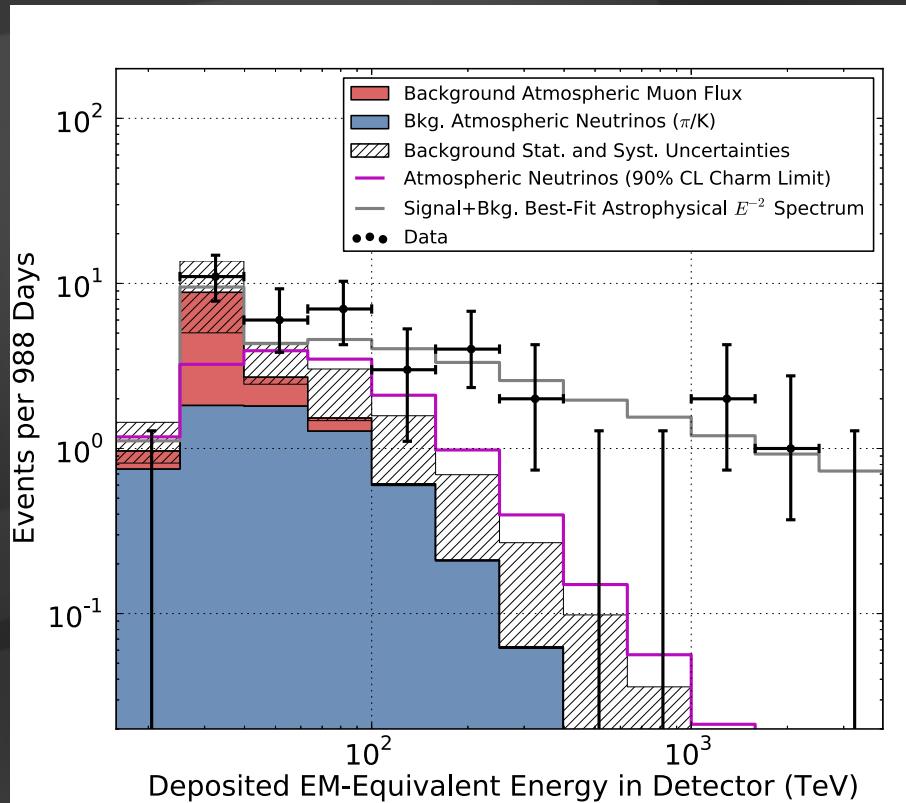
3 years





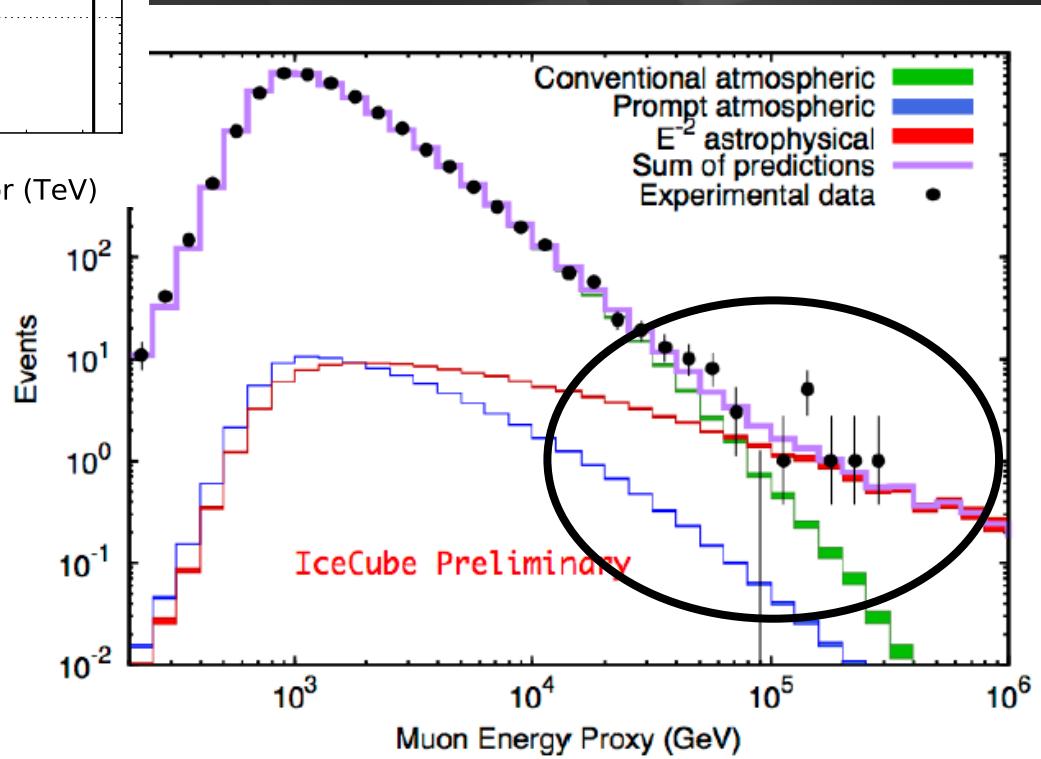
28 High Energy Events





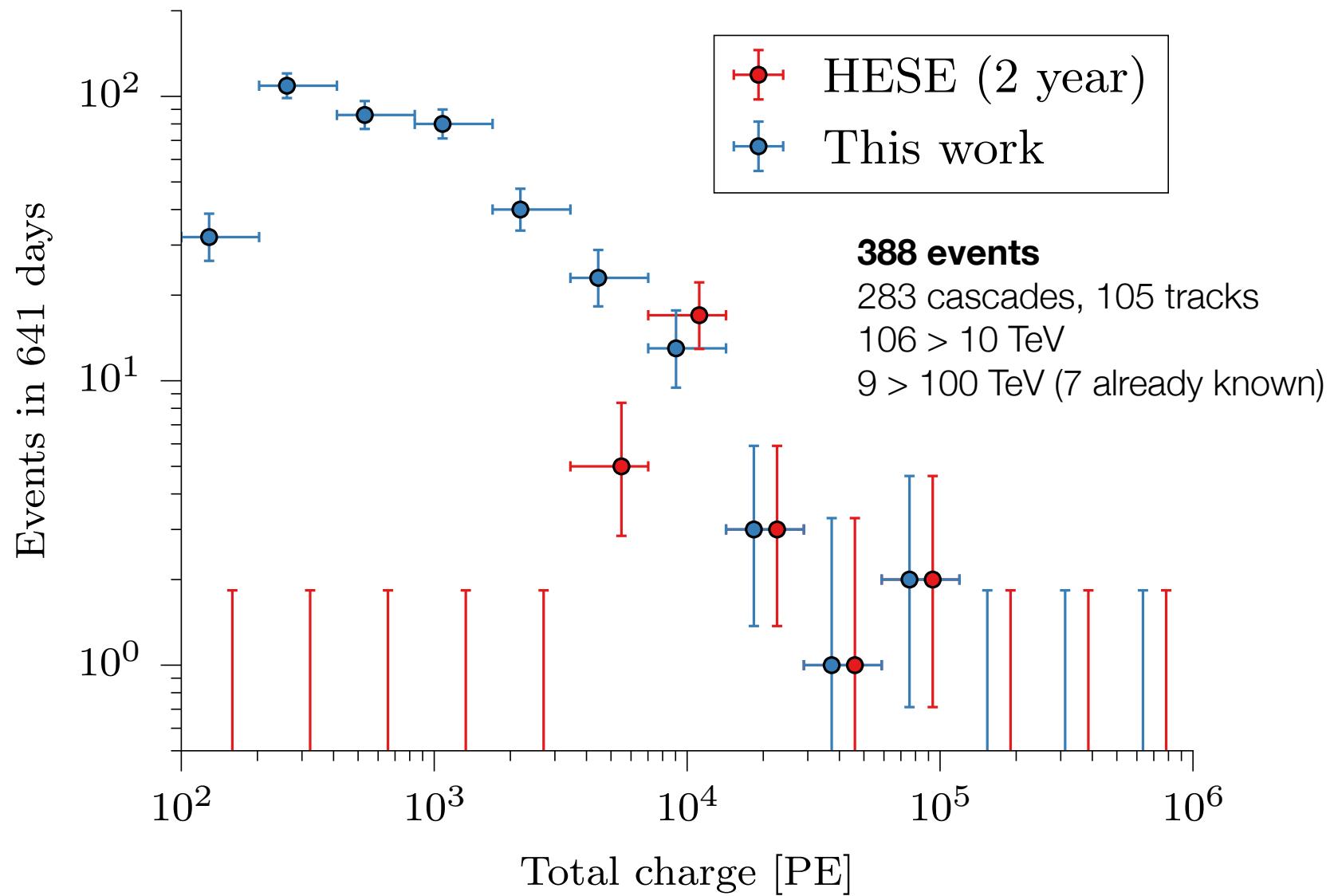
confirmation!
flux of muon neutrinos
through the Earth

↑
neutrinos of all flavors
interacting inside
IceCube

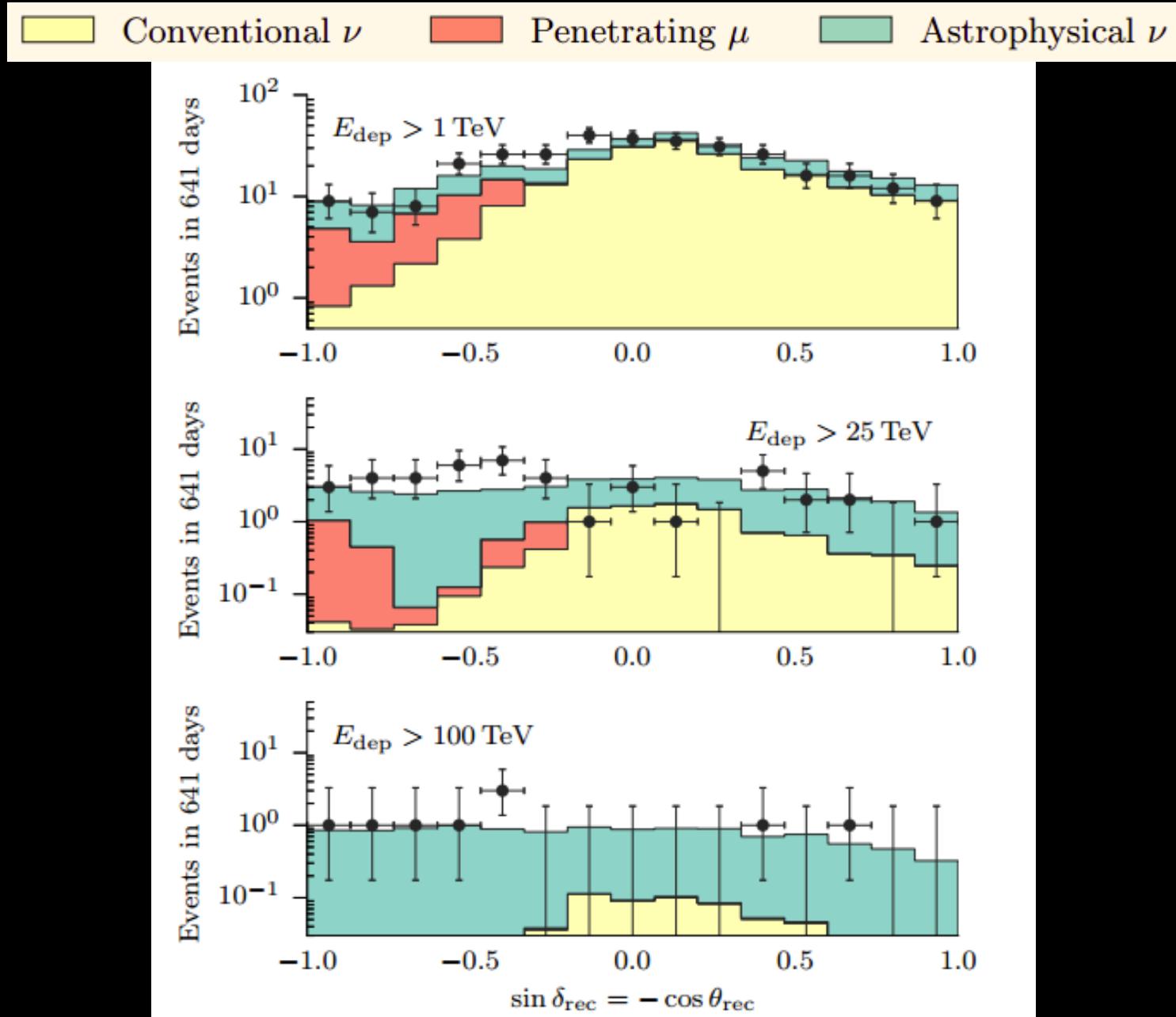


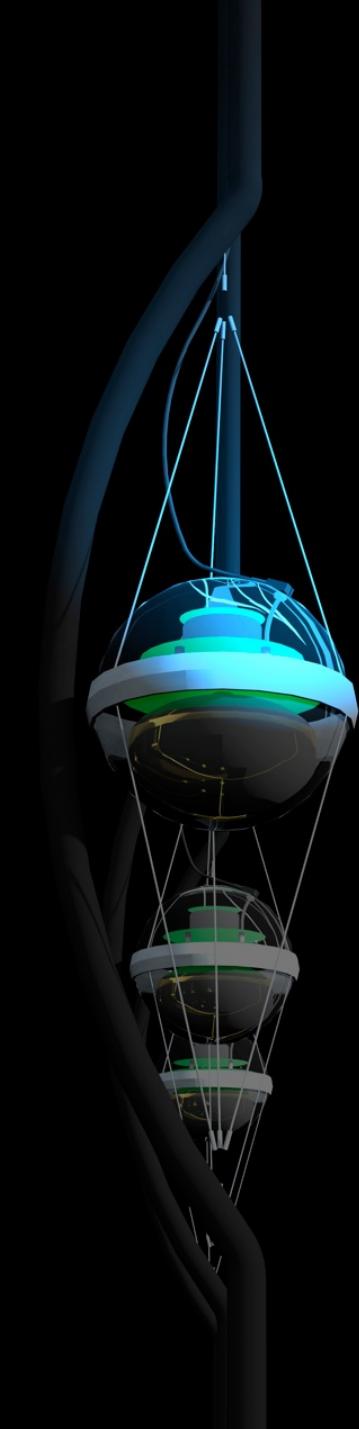
starting events 3 years

-- more sophisticated veto



arrival directions vs energy



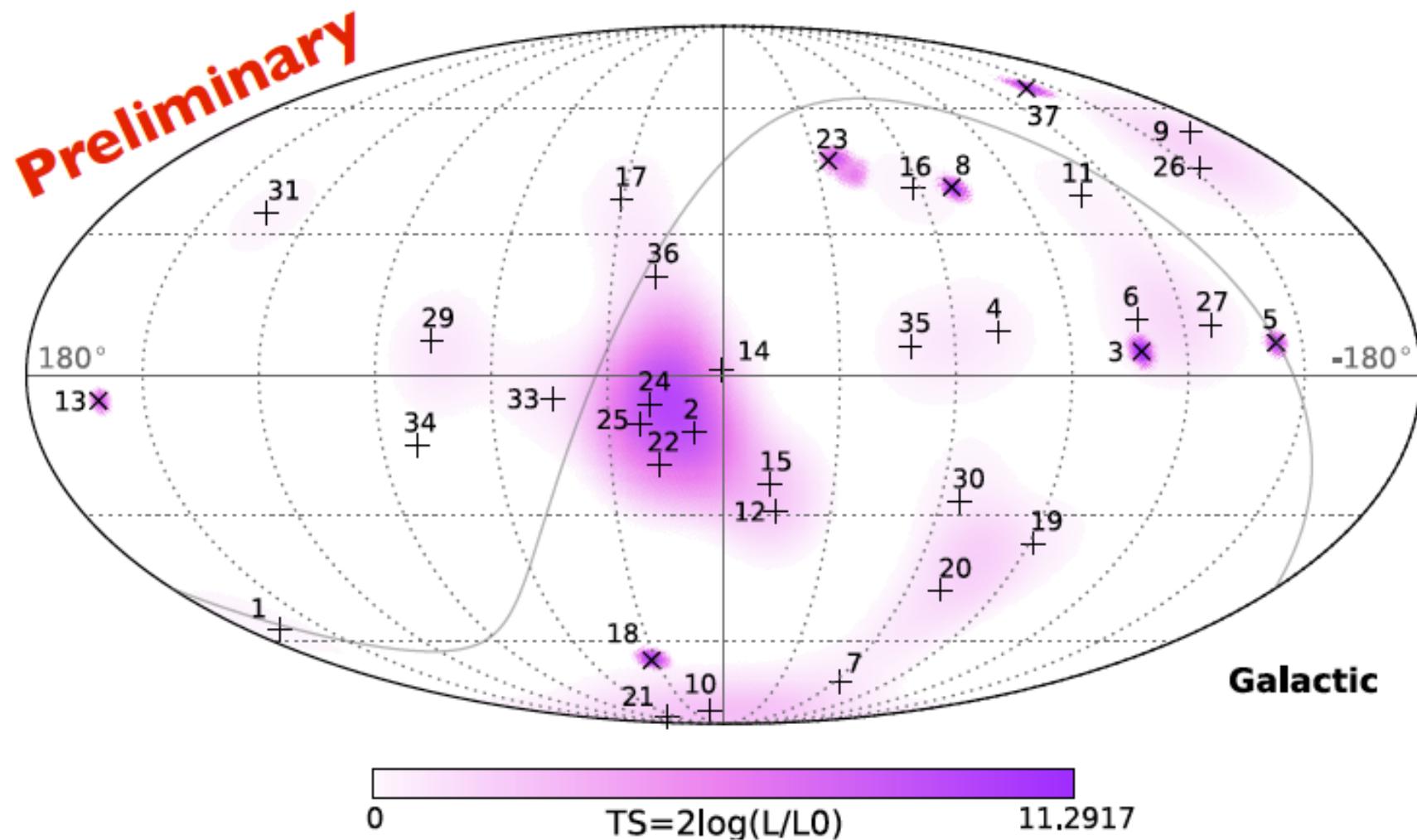


IceCube: the discovery of cosmic neutrinos

francis halzen

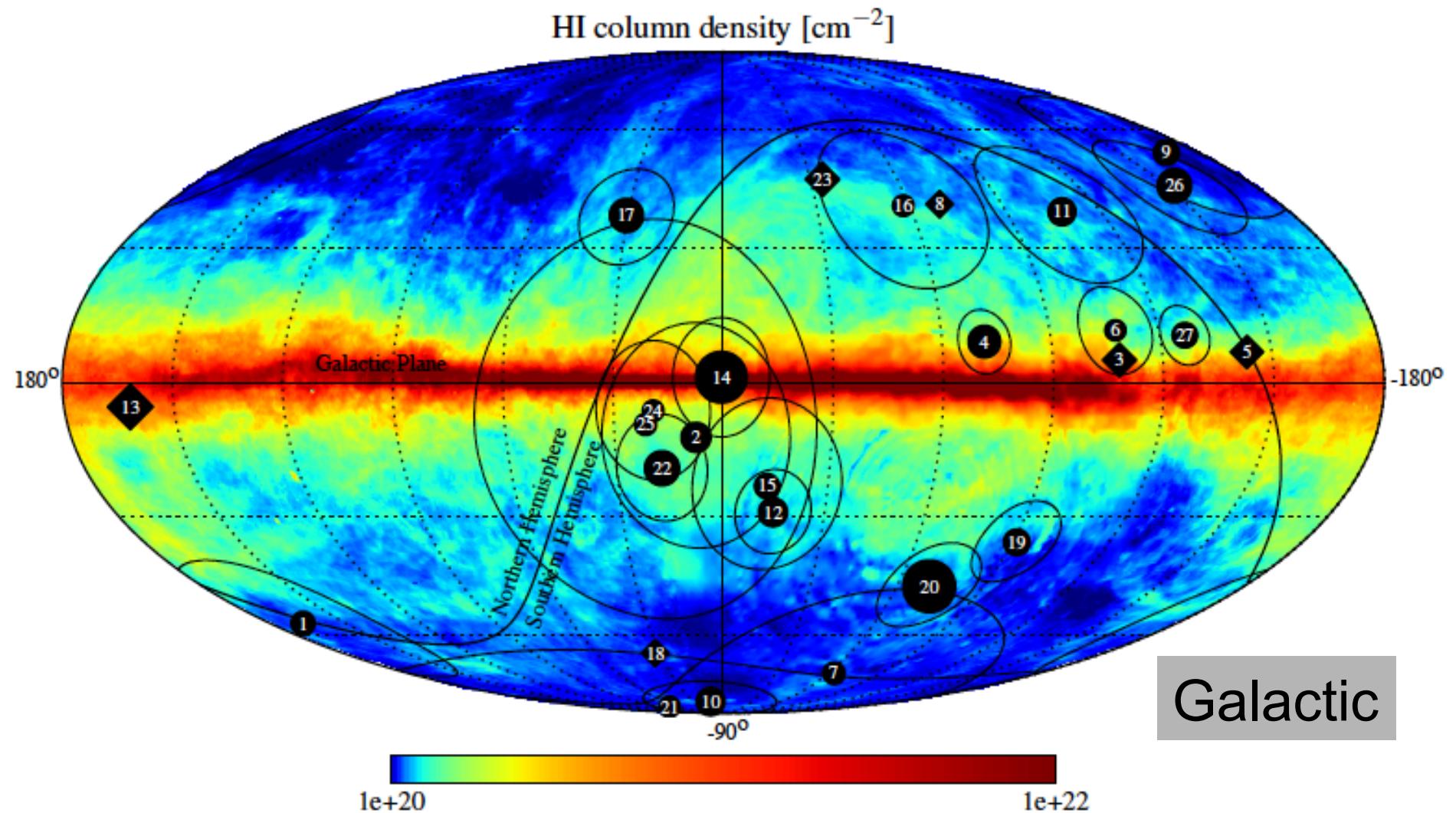
- cosmic ray accelerators
- IceCube a discovery instrument
- the discovery of cosmic neutrinos
- where do they come from?
- beyond IceCube

where do they come from (3 year data)?

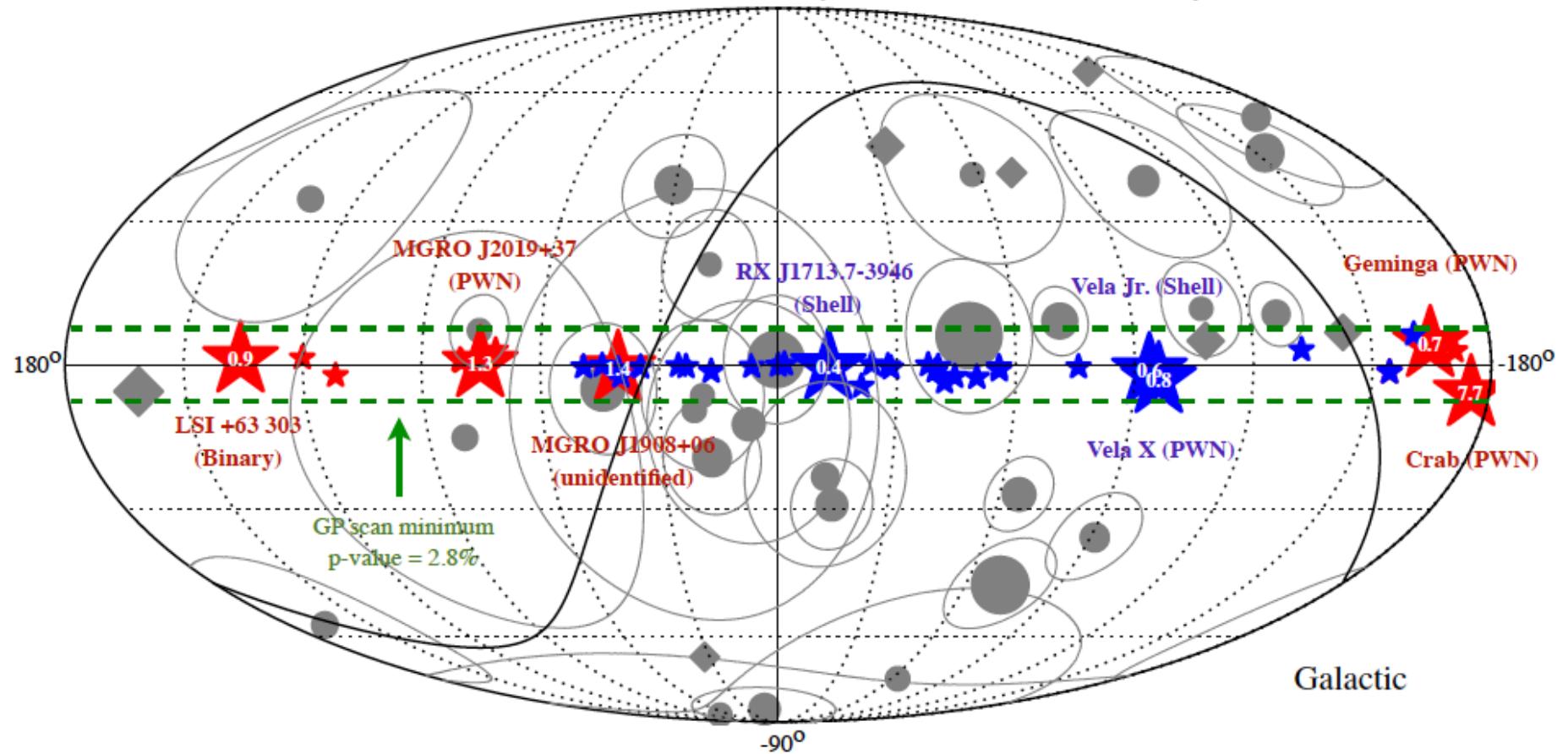


hottest spot 7.2%: consistent with diffuse flux with flavor 1:1:1?

correlation with Galactic plane: TS of 2.8% for a width of 7.5

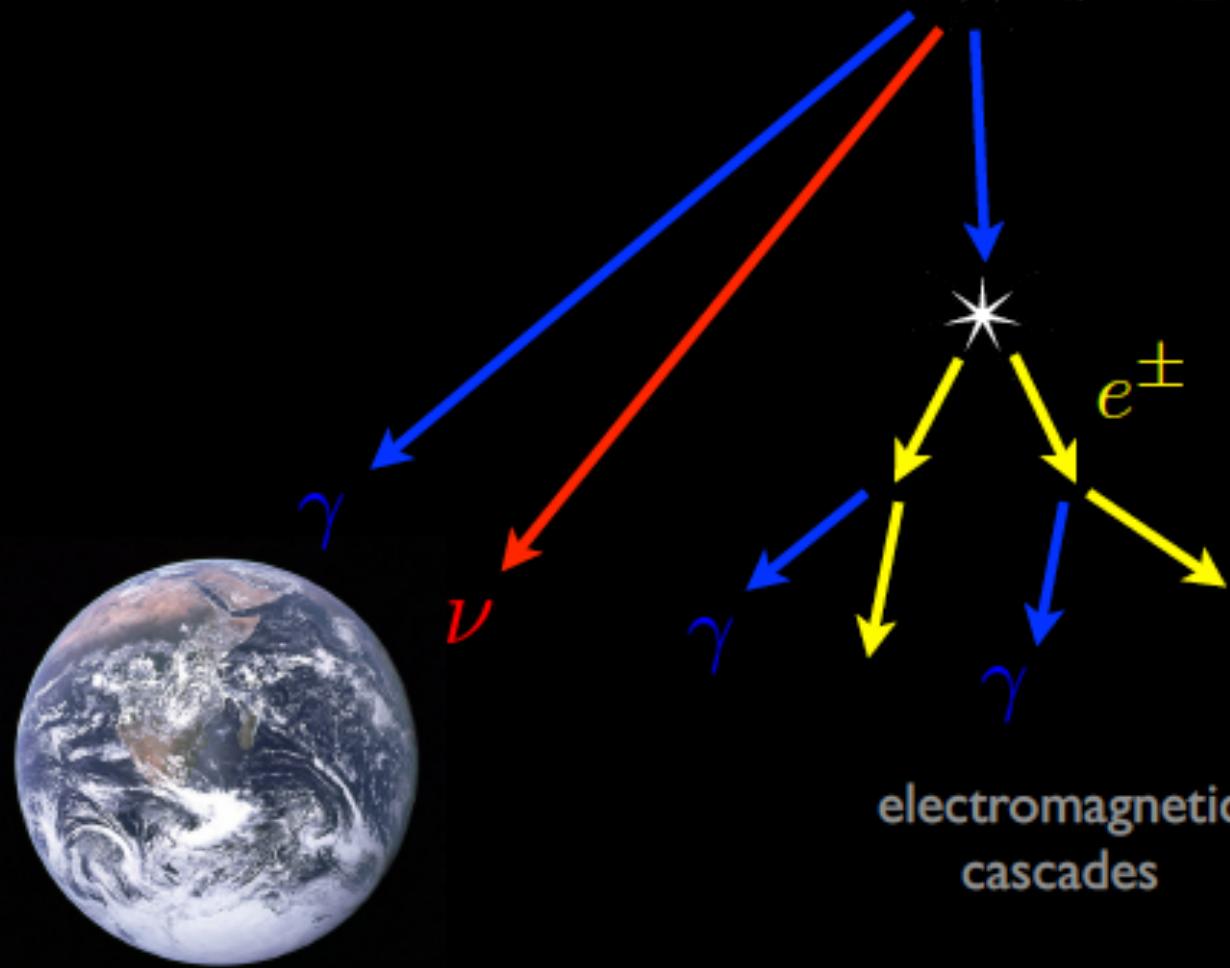
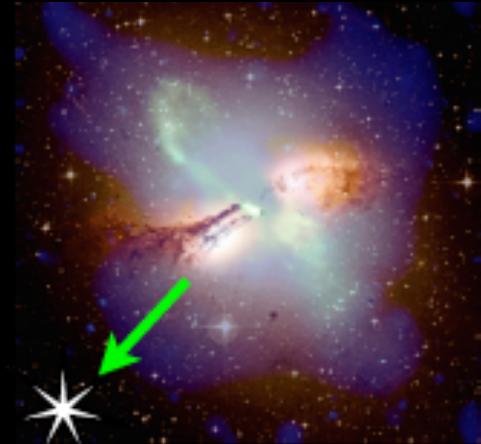


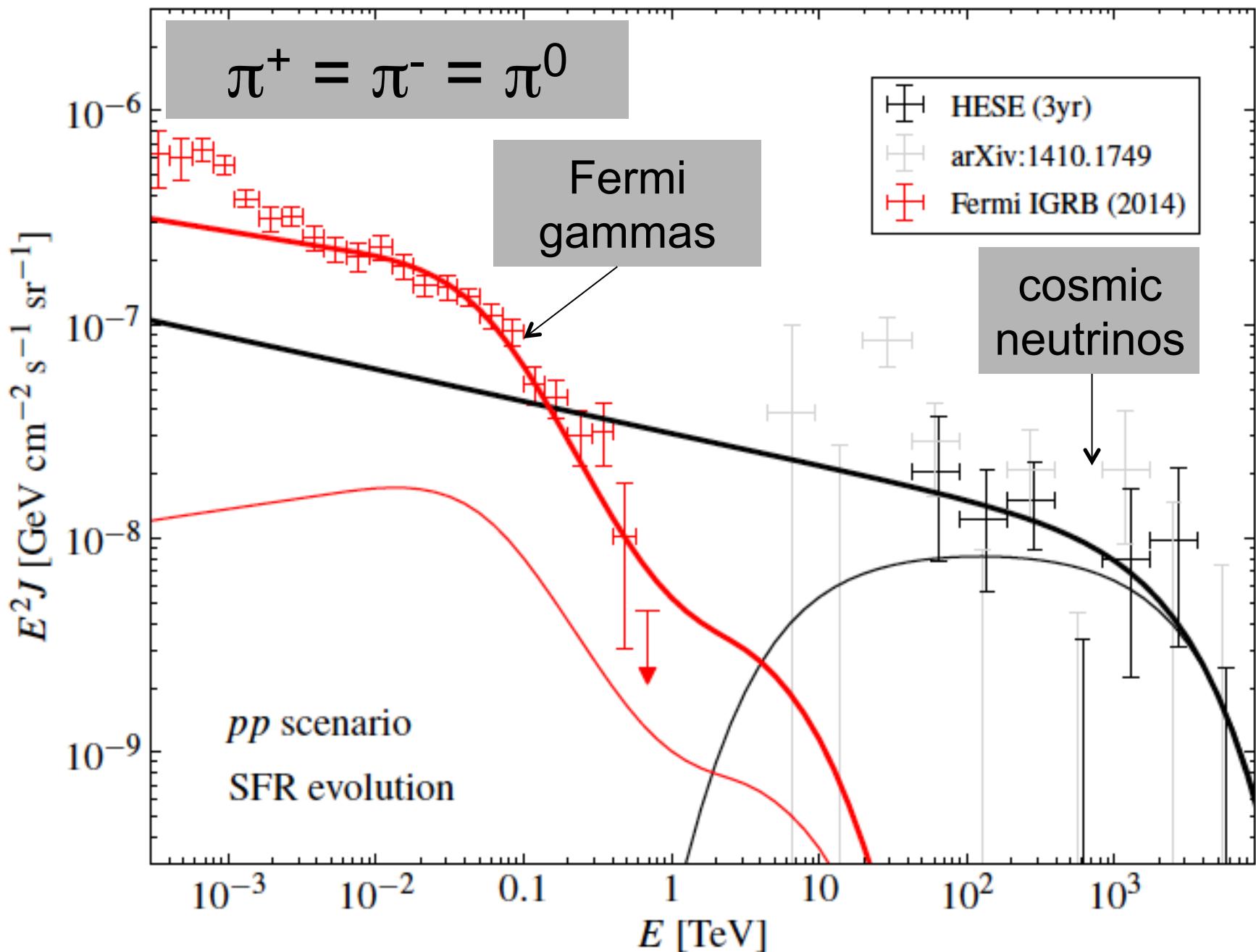
Galactic search with IceCube (red, 3yrs) & ANTARES (blue, 6yrs)



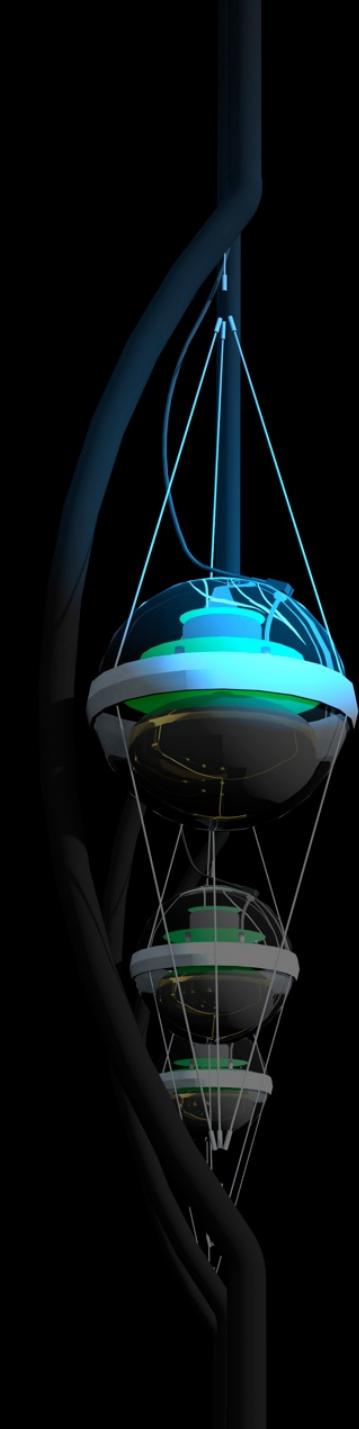
hadronic gamma rays ?

$$\pi^+ = \pi^- = \pi^0$$





- we have observed a flux of neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos
- hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe



IceCube: the discovery of cosmic neutrinos

francis halzen

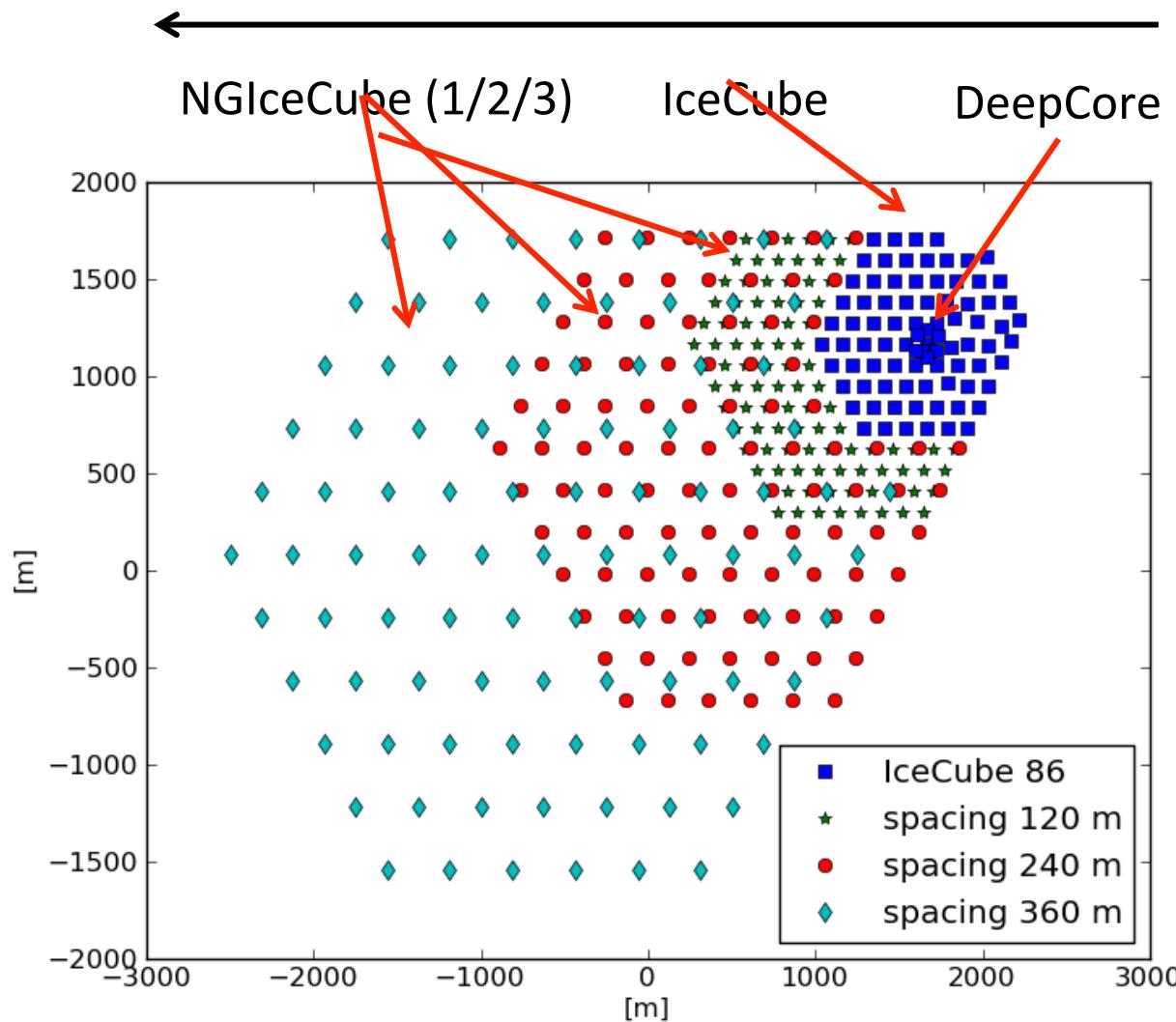
- cosmic ray accelerators
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a next-generation IceCube with a volume of 10 km³
and an angular resolution of 0.3 degrees will
identify the sources of a “diffuse” flux in several years
and guarantee astronomy

discovery instrument → astronomical telescope

measured optical properties → twice the string spacing

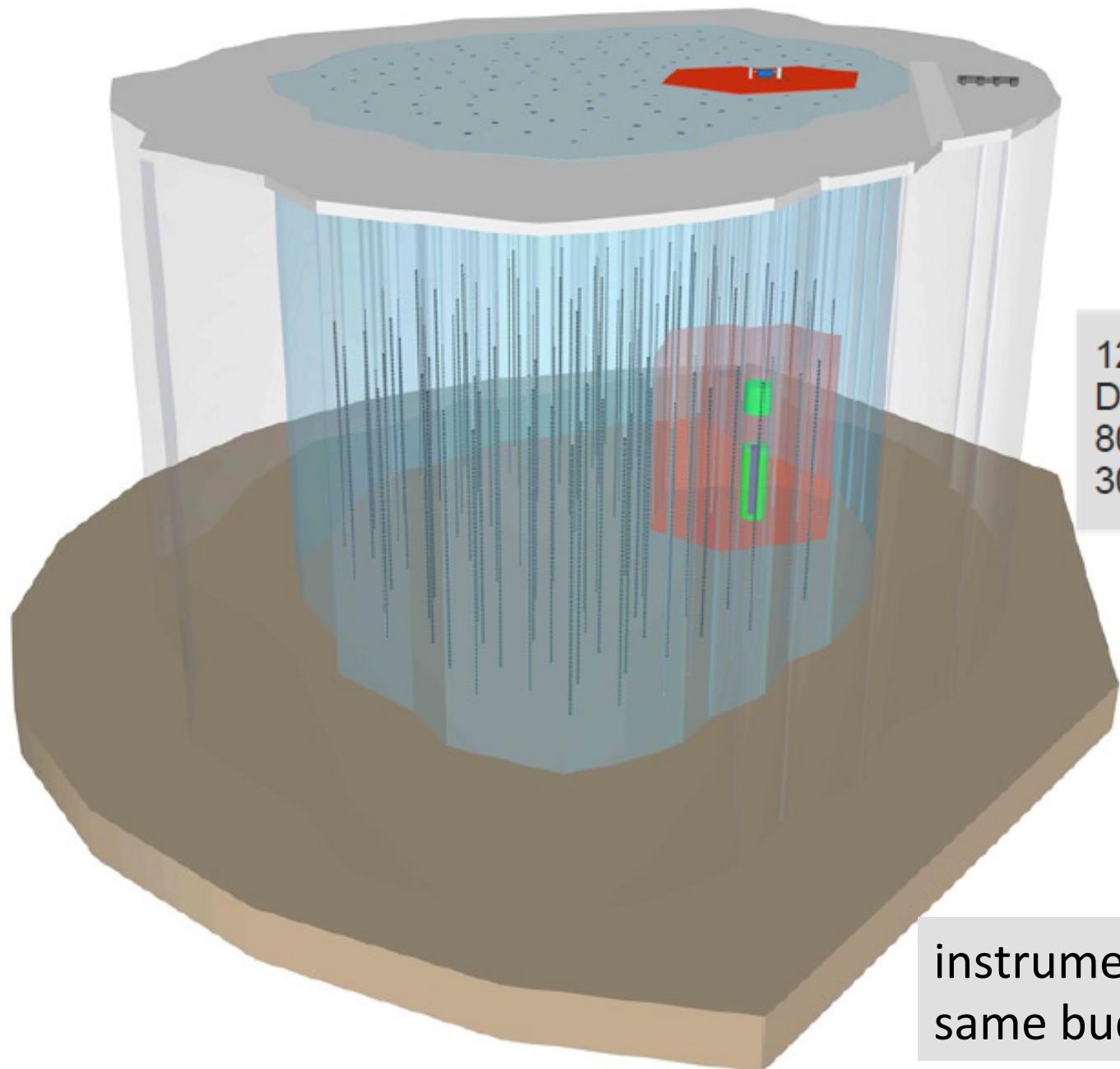
(increase in threshold not important: only eliminates energies where atmospheric background dominates)



Spacing 1 (120m):
IceCube (1 km^3)
+ 98 strings ($1,3 \text{ km}^3$)
= $2,3 \text{ km}^3$

Spacing 2 (240m):
IceCube (1 km^3)
+ 99 strings ($5,3 \text{ km}^3$)
= $6,3 \text{ km}^3$

Spacing 3 (360m):
IceCube (1 km^3)
+ 95 strings ($11,6 \text{ km}^3$)
= $12,6 \text{ km}^3$



120 strings
Depth 1.35 to 2.7 km
80 DOMs/string
300 m spacing

instrumented volume: x 10
same budget as IceCube

Next-Generation IceCube

- capitalize on discovery
- astronomy guaranteed
- ~ 120 strings: more sensors per string with higher quantum efficiency
- proven techniques, low risk
- flexibility of deployment per seasons: optimization
- cost similar to original detector

from discovery to astronomical telescopes:
parallel development in the Mediterranean

ANTARES → KM3NeT

Baikal → GVA

Conclusions

- we have observed a flux of neutrinos from the cosmos whose properties correspond in all respects to the flux anticipated from PeV-energy cosmic accelerators that radiate comparable energies in light and neutrinos
- hadronic accelerators are not a footnote to astronomy; they generate a significant fraction of the energy in the non-thermal Universe

The IceCube–PINGU Collaboration



International Funding Agencies

Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division

Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)